TRANSACTIONS OF

THE ROYAL SOCIETY OF CANADA

SECTION IV

GEOLOGICAL SCIENCES
INCLUDING MINERALOGY

THIRD SERIES—VOLUME XLVII—SECTION IV

JUNE, 1953

OTTAWA
THE ROYAL SOCIETY OF CANADA
1953

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA

VOLUME XLVII : SERIES III : JUNE, 1953

SECTION FOUR

Missi Series, Amisk Lake Area, Northern Saskatchewan

A. R. BYERS

Presented by J. B. MAWDSLEY, F.R.S.C.

THE Amisk Lake area lies a few miles west of the Manitoba-Saskatchewan boundary between latitudes 54° 30′ and 55° 00′. It is easily accessible by a highway fourteen miles long from Flin Flon, Manitoba.

Bruce (1918), who did the first systematic geological mapping of the area, separated the Precambrian strata into three divisions, applying the local names Amisk, Missi, and Kisseynew to volcanic, sedimentary, and gneissic rocks respectively. He divided the Missi into upper and lower parts on the basis of lithological character, the presence of pebbles of sedimentary rocks, and a boulder of conglomerate in the Upper Missi. He considered the Lower Missi later than the Amisk volcanic rocks because of structural and lithologic relations. Wright (1933) and Wright and Stockwell (1934) considered the Lower Missi sediments to be interbedded with the basic lavas (Wekusko group of Wright and Stockwell). The Upper Missi of Bruce became simply Missi and included the younger sediments unconformably overlying the Amisk. Recently, Harrison (1951, p. 8) in a summary of the stratigraphy of the Amisk Lake area, cites two personal communications that would indicate the Missi (Upper Missi of Bruce) is conformable and interbedded with the Amisk.

Since 1949 the Geological Branch of the Saskatchewan Department of Natural Resources has carried out a detailed survey of the Amisk-Wildnest Lake area. The writer agrees with Wright and Stockwell that Bruce's Lower Missi is a part of the Amisk group and the term Missi should be restricted to the series of younger sediments which unconformably overlie the Amisk.

Missi Series

Distribution and thickness

The Missi strata are confined to two separate synclinal structures and contact the underlying Amisk group along major fault zones or angular unconformities as shown in Fig. 1. A wide band of Missi

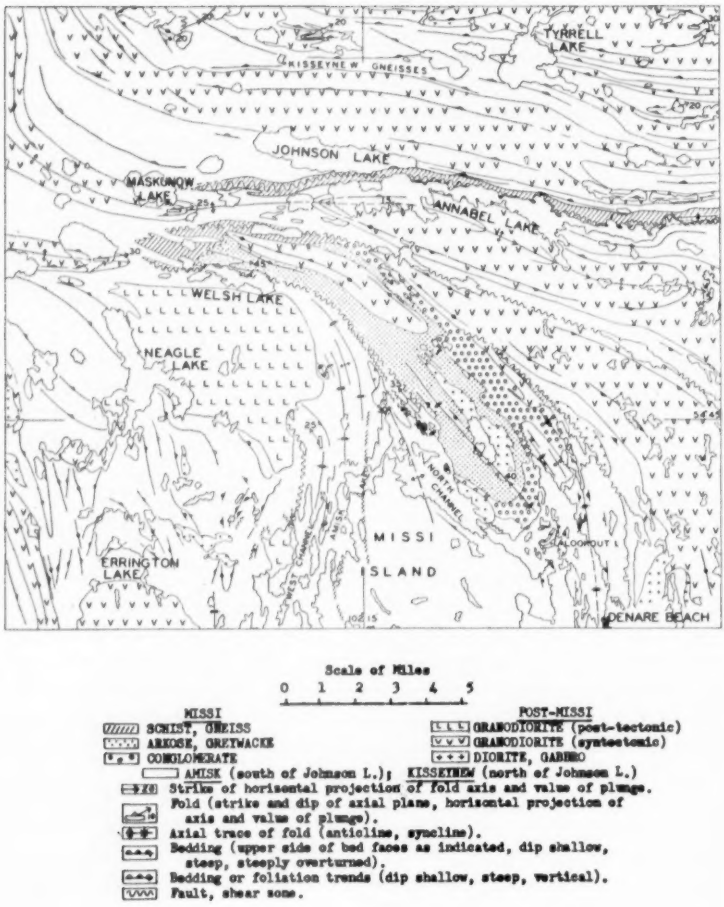

FIGURE 1. Geological sketch-map, Amisk Lake area, northern Saskatchewan.

sediments can be followed easily by an almost continuous series of large outcrops in a northwesterly direction from the northeast side of Amisk Lake to the area north of Welsh Lake. Northwest of Welsh Lake outcrops are scarce but from structural data it is improbable that the Missi sediments extend much farther to the west. A second narrower band, which forms the western extension of Missi sediments mapped by Tanton (1938) and Stockwell (1946) in the Flin Flon area, follows the north side of Annabel Lake and can be traced west of the lake by almost continuous outcrop for a distance of four miles. Small isolated remnants of Missi sediments occur in the southwest part of Missi Island, at the north end of North Channel, and to the northeast of Lookout Island along the east side of Amisk Lake.

Any estimate of the thickness of the Missi series is only approximate as the top has been eroded and the sediments are highly folded and faulted. However, in the vicinity of Amisk Lake north of Lookout Island, the structure is less complex with a syncline plunging northwest at 40 to 60 degrees and having vertical limbs on each flank of the fold. An estimated minimum thickness for the sediments in this area is 5000 feet with the lower 600 feet consisting mainly of coarse conglomerate. Ambrose (1936, p. 259) gives the minimum thickness of the Missi in the Flin Flon area as 5000 to 9000 feet.

Lithology

The basal conglomerate contains boulders and pebbles representing the rock-types of the underlying Amisk group. Common varieties are rhyolite, dacite, dacite porphyry, quartz and quartz-feldspar porphyry, quartz diorite, diorite porphyry, and greywacke. Less common are quartz, chert, jasper, greenstone, tuff, and a fine-grained, highly altered granodiorite. The source of the chert and jasper pebbles is unknown. Of thirty thin sections made from typical "granite-looking" pebbles and boulders, three had the texture and composition of a granodiorite and the remainder were recrystallized or altered quartz and quartz-feldspar porphyries related to the volcanic rocks of the Amisk group. The granodiorite is unlike any found in the area. Pebbles and boulders constitute 50 to 60 per cent of the rock but may be as high as 80 per cent. The matrix was a heterogeneous mixture of sand, silt, and clay. Where the conglomerate overlies basic lavas, chlorite is abundant. Elsewhere, quartz, feldspar, and mica are predominant and the composition ranges from arkose to greywacke.

The shape of the fragments in relatively undeformed conglomerate ranges from angular to well rounded and depends to some extent on the nature of the rock composing the fragments (Fig. 2). Thus many

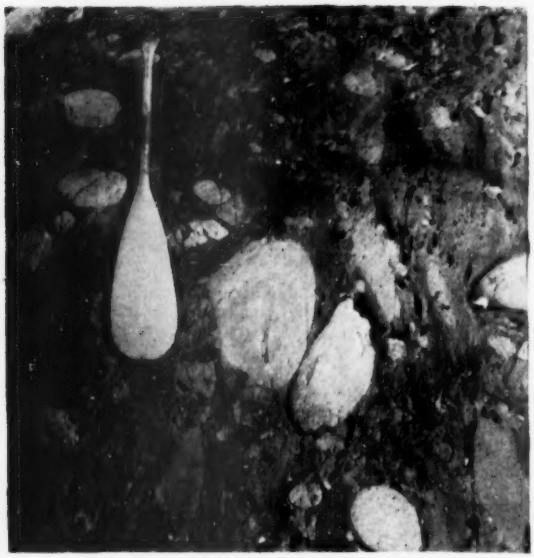

FIGURE 2. Relatively undeformed basal conglomerate, Lookout Island, Amisk Lake.

FIGURE 3. Sand lens in Missi conglomerate, north of Amisk Lake. Pebbles and boulders have been flattened and later contorted and bent by differential movements along closely spaced shearing planes.

FIGURE 4. Highly deformed Missi conglomerate, east end of Annabel Lake.

FIGURE 5. One limb of an open, steeply plunging shear fold showing displacement of marker beds in Missi arkose by slippage along rather widely spaced shearing planes. North of Amisk Lake.

of the fragments of greywacke and tuff are slab-like and nearly rectangular, whereas the more massive volcanic and intrusive rocks are subangular to rounded. With increased deformation the pebbles and boulders become flattened parallel to the foliation and elongated in the direction of the fold axis, and impart a marked lineation to the rock. In zones where shear folding has further deformed the conglomerate, the flattened pebbles and boulders become contorted and bent (Fig. 3). With extreme deformation, as observed north of Welsh Lake and at the east end of Annabel Lake, the boulders become so drawn out and flattened that they lose their identity and the conglomerate has the appearance of a rudely banded gneiss (Fig. 4).

Near the base the pebbles and boulders are poorly sorted and bedding becomes apparent only where fine-grained sand lenses are interstratified with the conglomerate (Fig. 3). These fine-grained bands range from six inches to several feet thick and have a length up to 100 feet. Towards the top of the conglomerate these bands become thicker and more numerous and alternate with layers of conglomerate. A few of these conglomerate layers are bedded and in some beds grain gradation is conspicuous with pebbles at the bottom and sand at the top. Because of this interbanding no sharp boundary can be drawn between conglomerate and the overlying sediments.

The basal conglomerate passes upward into interbanded arkose and greywacke; the latter becomes more abundant towards the top of the series. The arkose is fine to coarse grained, pink to buff coloured, and consists of quartz, feldspar, and white mica. In certain areas it contains rounded pebbles of quartz, rhyolite, quartz and quartz-feldspar porphyries. The greywacke is fine to medium grained, grey to dark grey and consists of quartz, feldspar, biotite, and chlorite. In thin section the arkose possesses a clastic texture modified by recrystallization and the development of a foliated fabric. The larger grains consist of quartz, highly altered potash feldspar and plagioclase, altered fragments of acidic volcanic rocks, and chert. These are embedded in a very fine-grained matrix of quartz and sericite with minor carbonate, biotite, and epidote. Microscopically, the texture of the greywacke is similar but the amount of matrix is greater. There is also a higher proportion of plagioclase, biotite, and chlorite. The composition ranges from subgreywacke to greywacke (Krumbein and Sloss. 1951, pp. 133–4).

The arkose and greywacke are well stratified. Crossbedding is common but graded bedding is rare in the arkose, whereas the opposite is true for the greywacke. Both types of bedding can be observed only in areas of mild deformation and are quickly destroyed by the develop-

ment of a very marked foliation or schistosity. This is especially true for the sediments in the northern band that passes along the north side of Annabel Lake.

In both bands the sediments become progressively altered and recrystallized towards the west, and grade into sericite or biotite schists and gneisses. The sericite schist and gneiss are fine-grained, grey to dark grey rocks containing aggregates of sericite that frequently form knots or blebs slightly elongated within the plane of schistosity. These blebs are very conspicious on fresh surfaces which parallel the foliation and frequently attain a diameter of one-half to three-quarters of an inch. Some biotite is usually present and locally a few small garnets. Microscopically, the minerals are quartz, oligoclase-andesine, sericite, and smaller amounts of biotite, chlorite, garnet, magnetite, and apatite. The original clastic texture is completely changed by granulation to a cataclastic one which shows gradations from partial to almost complete recrystallization of the mineral constituents. Some thin sections show shear cleavages, 0.2 to 0.3 millimetres apart, along which movement has taken place as indicated by development of ultramylonite now partially recrystallized to chlorite and sericite. This shear cleavage is cut by a later more widely spaced fracture cleavage which, in hand specimens, is marked by minute crenulations on the planes of schistosity. The biotite schist and gneiss are medium to dark grey and weather a light grey to pinkish grey. Banding in the gneiss is caused mainly by differences in the amount of biotite within adjacent bands and is more pronounced than the banding in the sericite gneiss. In addition to the biotite, the schist and gneiss contain quartz, feldspar, sericite, and a few scattered garnets. Thin sections show the presence of magnetite, apatite, epidote, zircon, hornblende, and pyrite. The texture and microstructures are similar to those in the sericite schist and gneiss. In places the sericite-rich and biotite-rich rocks are interbanded.

Structures

The folding of the Missi as well as the Amisk is essentially isoclinal with the development of axial plane cleavage. They have both undergone essentially the same amount of deformation and on a broad scale are structurally conformable. The northern band of Missi sediments is bounded on the north and south by strata of the Amisk group and forms the core of a syncline which is the western continuation of the Flin Flon syncline that lies to the east and outside the Amisk Lake area. Structural criteria which indicate the synclinal

nature of this structure have only been observed east of Annabel Lake where deformation has not completely destroyed the primary sedimentary structures. The fold is isoclinal and overturned to the south. Although direct evidence is lacking, the plunge is probably at a low angle to the east. The syncline is traversed throughout its length by a zone of intense shearing which has altered the sediments to a highly crenulated and schistose quartz-feldspar-sericite schist. Movement along this zone has probably been great. A study of thin sections shows that the sediments have been altered to mylonite and ultramylonite over widths of 200 to 700 feet. That this zone of mylonitization is not simply the result of intense deformation of a weak member of the Missi series is clearly shown by the transgression of the band of shearing from the south side of the syncline at its east end to the north side at the west end. The shear zone dips 45 to 65 degrees north and steeply plunging S-shaped folds indicate that the movement was reverse with the north side being moved up and to the southwest.

The southern band of Missi sediments occupies an isoclinal elongated basin intruded by discordant masses of granodiorite and gabbro. The structure extends northwesterly from Lookout Island in Amisk Lake to the area south of Maskunow Lake. The southwest limb is bounded and partially cut off by a major fault zone. The north limb is in part bounded by two other faults with the northern one cutting and eliminating a section of the limb in the area north of Welsh Lake. Primary structures, especially crossbedding and graded bedding, show that the two limbs face inward. However, within the major fold there are numerous minor folds which belong to two distinct types. One type plunges at approximately the same angle as the major structure, namely, about 40 degrees northwest near the southeast end and 35 degrees east towards the west end of the synclinal basin. The folds are either S- or Z-shaped depending on which flank of the main syncline they are located on, that is, they bear the same relation to the major fold as do drag folds. The second type of fold plunges at angles over 70 degrees and the attitude and shape of the fold bear no relation to the major syncline. These steeply plunging folds are invariably associated with bands of high schistosity or intense shearing which parallel the axial plane foliation of the major syncline. The width of the bands and consequently the size of the folds ranges from a few tens of feet to several hundred feet. In many outcrops it is apparent that slippage along the cleavage planes, as measured by the displacement of marker beds (Fig. 5), is sufficient to account partially or wholly for the form of the fold. The spacing of the planes of slippage

ranges from about one foot to a minute fraction of an inch, the latter being more common. These folds may be referred to as slip or shear folds as defined by Knopf and Ingerson (1938, pp. 157–9).

The trough at both ends is also complicated by minor folds which plunge at about the same angle as the main syncline, namely, 40 degrees northwest at the southeast end and 35 degrees east at the west end of the syncline.

Relation to Amisk Group

The contact of the Missi Series with the Amisk group is well exposed in the vicinity of Lookout Island, Amisk Lake. Pillowed and massive andesite is overlain with structural unconformity by Missi conglomerate. The volcanic flows south of Lookout Island strike nearly north-south, dip steeply and face east. The conglomerate and arkose strike east-west, face and dip to the north. The universal presence of pebbles and boulders from the underlying Amisk rocks in the Missi sediments also clearly indicates the presence of unconformity between the two.

The relative position of outcrops of Amisk and Missi rocks in the same area indicates that the Missi was deposited on a highly irregular surface. This in part, at least, accounts for several of the isolated patches of Missi conglomerate found resting on the Amisk volcanic flows. However, other isolated remnants like the band at the north end of North Channel and on the east side of Amisk Lake, have been preserved by either down-folding or faulting.

Conditions of Deposition, Source, and Age

The conglomerate at the base of the Missi, with the exception of a few pebbles of chert, jasper, and granodiorite is composed entirely of debris derived from the underlying strata of the Amisk group. Even the overlying arkose contains small rounded grains and fragments of acidic lavas or intrusive porphyries related to the volcanic series. The poorly sorted, lithologically heterogeneous nature and the thickness of the conglomerate are indicative of deposition in a rapidly subsiding basin, mainly by torrential fluvial action carrying coarse clastic material from uplifted adjacent source areas. Strong current action and deposition in shallow water are also indicated by the numerous channel scours with subsequent infilling by sands to produce the interbedded sandy lenses in the conglomerate, by the abundance of crossbedding in the arkosic sediments, and by the roundness and smoothness of many of the cobbles and boulders.

Although in local detail there is structural discordance between the Amisk and Missi strata as found in the vicinity of Lookout Island, the

regional structural relation between the two is one of structural conformity. It is believed, therefore, that the Missi strata were deposited shortly after the close of the period of Amisk volcanism and, although minor folding affected the Amisk rocks previous to the commencement of the laying down of the Missi sediments, there is no major break in the geologic history of the area.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA

VOLUME XLVII : SERIES III : JUNE, 1953

SECTION FOUR

Glacial Features of Ungava from Air Photographs

MARY C. V. DOUGLAS and R. N. DRUMMOND

Presented by J. T. WILSON, F.R.S.C.

THE first attempts to map most areas have been made by explorers travelling along convenient routes. For most of Ungava that is all the mapping that has yet been done, since the second stage of systematic mapping by successive areas has only recently started along the southern coast and along the Labrador Trough which runs approximately north and south through Knob Lake (Dufresne, 1929; Gilbert, 1951). In particular, observations upon glacial geology have been few and scattered (Flint, 1945).

During the past ten years or so, air photographs have been taken of all Ungava and topographical maps have been prepared from them. Many who have flown across the area have noticed how conspicuous are the eskers and other glacial features, the areas of outcrop, and the changes in vegetation from south to north. This suggested the project of plotting for the entire Ungava peninsula those geological features which could be distinguished on air photographs.

Air photographs have proved to be an efficient and easy means of mapping many glacial and structural features quickly. These have included drumlins and less regular ridges and furrows apparently formed by the ice flow, eskers, moraines, raised beaches, and alluvial deposits as well as foliation, faults, and fractures in the bedrock. Rock exposure was also mapped using three broad categories: no visible outcrop, less than, and more than 30 per cent outcrop. This information was plotted on eight-mile to one-inch scale base maps of the National Topographical Series, twenty-seven of which cover the mapped area.

To date only the map of drumlins and similar indications of glacial ice flow has been compiled. Although it has not yet been completed for the whole peninsula, the pattern thus far shown is felt to merit presentation at this time (Fig. 1). Later it is intended to publish maps for the whole peninsula showing other features.

Ground observations will certainly be necessary before the Pleistocene history of Ungava is unravelled. It is hoped that these maps

will assist ground work and that they may inspire further and more detailed stereoscopic examination of vertical air photographs.

In the meantime this survey is far more complete than any other and certain conclusions and suggestions may be drawn from it, however preliminary and tentative they may be. Some confidence in these conclusions may be felt from the fact that the directions shown on this map have been carefully compared with those shown on the Glacial Map of North America (Flint, 1945). Nearly all of those shown by Flint are parallel or approximately parallel with some of those on Fig. 1, with the exception of some pointing north at the western entrance to Hudson Strait for which no counterparts were found. This correlation extends even to finding two sets of drumlins near Knob Lake parallel with the two sets of glacial striae there shown by Flint and to the two directions of glaciation apparently due to different lobes of the ice south of James Bay.

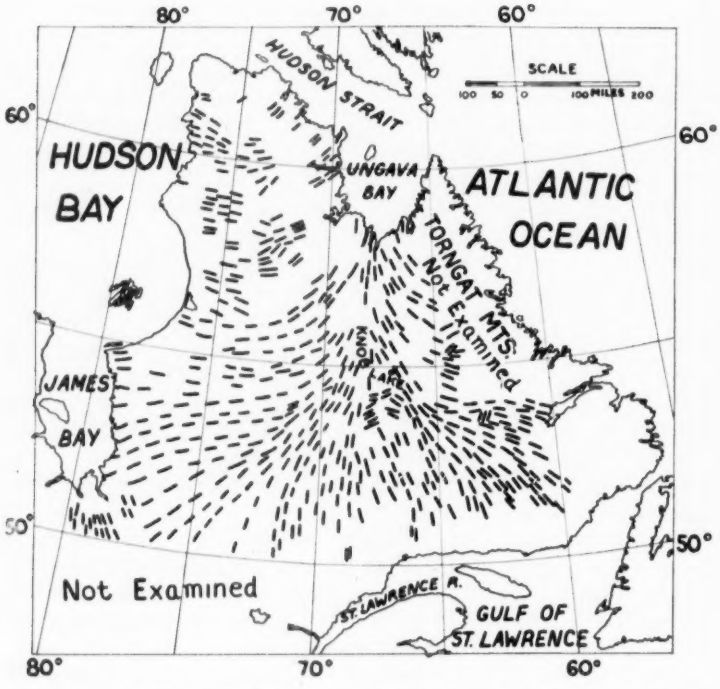

FIGURE 1.—Directions of drumlins and glacial furrows in Ungava as plotted from air photographs.

The pattern of drumlins and drumlinoids sheds light upon the movements of the continental ice sheets and upon the position of ice accumulation. The particular value of drumlins is that they indicate the orientation of ice movement parallel to them. Drumlins show only the direction of the most recent advance in a particular area, as those formed by an earlier movement have presumably been obliterated, except for a few protected remnants. Although the drumlins are parallel to the direction of movement of the ice, it is not always possible to determine the sense of direction from them. This is especially true when they are seen on air photographs taken at 20,000 feet. It is, therefore, only possible to postulate the direction towards which the ice moved and the position of the centres of accumulation.

The ground observations upon which such ideas have previously

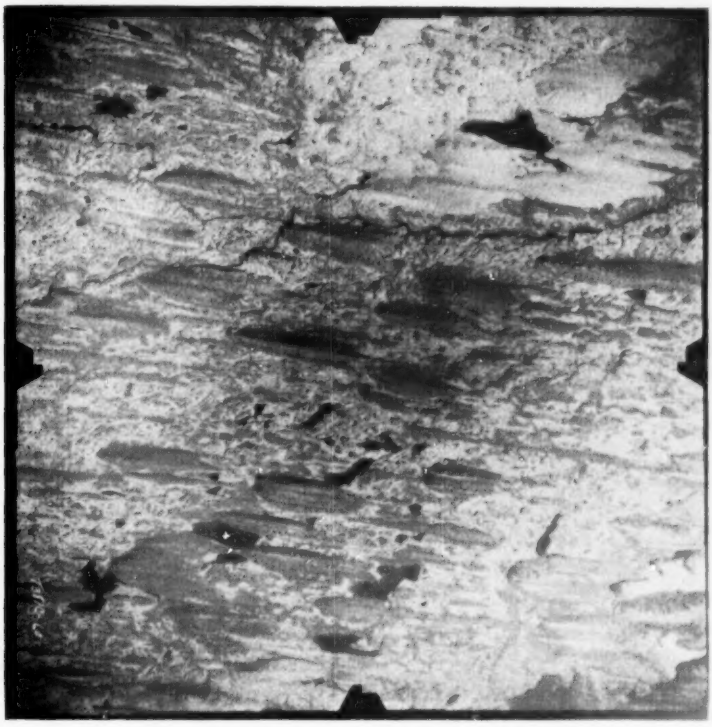

FIGURE 2.—Vertical photograph of drumlins near Goose Bay airport at latitude 53° 45′N. and longitude 61° 25′W. Royal Canadian Air Force photograph T 381C-60.

been based are so few and scattered that at least two very different interpretations have been placed upon them. The older view was that ice which "covered the Quebec-Labrador peninsula was almost wholly derived from the Labradorean sheet, whose centre of accumulation was east of James Bay. Coleman reports (1926, p. 17) that Low, to whom our knowledge of the glacial geology of the interior of the peninsula is almost entirely due, determined that the centre of accumulation was not stationary but moved gradually northward—from this central area the ice moved out more or less radially" (Dresser and Denis, 1944, p. 23).

The second view, which has been advanced by Flint (1943) largely on climatological grounds, was that the original accumulation took

FIGURE 3.—Oblique view looking east near south end of Ungava Bay showing direction of glaciation striking NNE.-SSW. Royal Canadian Air Force photograph T 385R-139.

place on the Torngat Mountains from which it moved westward. He has maintained that the greater height, higher latitude, and closer proximity to Atlantic precipitation would have made them a more probable locus of ice accumulation than any other in the peninsula.

The pattern obtained by the study of air photographs is far more complete and its most striking feature is the apparently continuous lines of drumlins radiating out from Ungava Bay, suggesting that the ice started accumulating in Baffin Island and that, as the ice increased, its movement was away from the north until it radiated southward over the entire peninsula. The same arguments which were used by Flint and the position of present-day ice caps make this idea seem all the more probable.

On the other hand, many of the ground observations suggest that the ice moved radially off the land. In the area between Ungava Bay and Knob Lake, in the centre of the peninsula, most striae and boulder fans are said to indicate that the ice moved northwards into the bay. If so, the problem is considerably more complicated, as the pattern can only be explained by a number of centres: one in the vicinity of the Knob Lake and others to account for drumlins east and west of Ungava Bay. Southward from Knob Lake, ground observations show that the ice radiated out southward either from a Knob Lake centre or one further north. On the other hand such a centre does not explain the seemingly continuous pattern spreading out from Ungava Bay across most of the peninsula.

In several other parts of the peninsula, namely west of Ungava Bay, around Knob Lake, and along the eastern margins of the mapped area, there are drumlins which do not fit into the over-all pattern, suggesting previous advances of the ice from different directions. Also, south of James Bay, at the southwestern corner of the mapped area, there is a field of drumlins running northwest-southeast and north-south which must have been formed by another centre or lobe not directly related to the ice sheet which covered Ungava.

In view of the difficulty of determining the direction of ice movement even in the field, especially when the conditions of exploratory work are considered and the preconceived ideas possibly held by some of the observers, it seems right to suggest that the problem is an open one but that it is possible that the Labradorean or Ungava ice sheet started accumulating in Baffin Island.

Finally, it is clear from the above evidence that it may be necessary to revise some of the ideas concerning the history of the Pleistocene in Ungava and in particular that further work must be done before a

new hypothesis can be formulated to explain the observed data fully.

The authors wish to express their thanks to the Defence Research Board of Canada for supporting the project through the Arctic Institute of North America, to J. T. Wilson who suggested and supervised the project and read this paper critically, to Jane A. McCarthy and Joan Ruddell who participated in the work, and to Dorothy Perryman and Rosamund Jackson for assistance in preparing the manuscript.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA

VOLUME XLVII : SERIES III : JUNE, 1953

SECTION FOUR

An Analysis of Downpunching

H. S. HEAPS

Presented by G. VIBERT DOUGLAS, F.R.S.C.

THE aim of the present paper is to present in a summarized form some quantitative results of a theoretical analysis of the stresses arising in the crust of the earth due to the effect of a surface load, such as an ice-cap. The crust is assumed to behave as a perfectly elastic material of constant density throughout, and to be supported along its lower surface by a fluid-like material of density different from that of the crust. The lower surface of the crust is thus subject to isostatic compensation whenever a load is borne by the upper surface. The analysis assumes that the ice-cap is symmetrical about some vertical axis. A similar treatment for a very long ice-cap of uniform cross-section follows an almost identical procedure; in the problem of this paper the mathematical approach is by way of the Hankel transform, while for an ice-cap of constant cross-section the Fourier transform is used.

The method may be applied to determine the state of stress below any ice-cap symmetrical about a vertical axis, and so could be used in the case of a conical or hemispherical cap. However, the computations are so tedious that it was deemed sufficient to treat only one case, a cylindrical cap being the one chosen as an example.

The upper surface of the crust is assumed to be subject to a loading of $p(r)$ per unit area, where r is the radial distance outward from the axis of symmetry of the load. The lower surface experiences an upthrust which, for unit downward displacement at any place, is equal to the amount by which the density of the supporting medium exceeds that of the crust.

In order to introduce a suitable coordinate system, let the origin be taken on the axis of symmetry of the load and at a point half way through the crust. Let the z-axis be downward from the origin and let the θ direction denote a rotation about the vertical z-axis. If half the thickness of the crust is taken as the unit of length then the r and z coordinates are dimensionless.

Under the applied surface forces the stresses at any point in the crust may be written in terms of the following function, the Hankel transform of the surface load,

$$q(s) = \int_0^\infty p(r) \,.\, r \,.\, J_0(sr) \,.\, dr.$$

The normal stresses per square cm. in the r, z, θ directions then take the form (using the method of Sneddon, 1951, as applied to symmetrical stress systems):

$$\tau_r = \int_0^\infty F_r(s, z) q \,.\, (s) \,.\, J_0(sr) \,.\, ds - (2/r) \int_0^\infty G(s, z) \,.\, q(s) \,.\, J_1(sr) \,.ds$$

$$\tau_z = \int_0^\infty F_z(s, z) \,.\, q(s) \,.\, J_0(sr) \,.\, ds$$

$$\tau_\theta = -4\sigma \int_0^\infty F_\theta(s, z) \,.\, q(s) \,.\, J_0(sr) \,.\, ds + (2/r) \int_0^\infty G(s, z) \,.\, q(s) \,.\, J_1(sr) \,.\, ds$$

where F_r, F_z, F_θ, G are very complicated expressions in s and z and will not be reproduced here. All of these functions depend upon the value of Poisson's ratio for the crust, and also upon the density difference between the material of the crust and the underlying medium. The shear stress τ_{rz} acting upon the horizontal plane at any point is given in the form

$$\tau_{rz} = \int_0^\infty F_{rz}(s, z) \,.\, q(s) \,.\, J_1(sr) \,.\, ds.$$

The integrals involved in the expressions for the stresses must be evaluated numerically and involve a large amount of computational labour. The stresses τ_r, τ_z, τ_θ, τ_{rz}, having been computed at any point, the three principal stresses may be calculated as

$$\tau_\theta, \tfrac{1}{2}(\tau_r + \tau_z) \pm \left[(\tfrac{1}{2}\tau_r - \tfrac{1}{2}\tau_z)^2 + \tau_{rz}^2 \right]^{\frac{1}{2}},$$

and the maximum shearing stress at any point is

$$\tfrac{1}{2}(\text{max. princ. stress} - \text{min. princ. stress}).$$

The analysis outlined above has been applied to the example of a crust of thickness 40 km. supporting a load in the form of a circular cylinder of vertical axis and diameter 400 km.; the material below the crust has been assumed to have a density of 1 gm. per cu. cm. in excess of that of the crust. Poisson's ratio and the modulus of elasticity of the crust are taken as 0.25 and 7×10^{11} respectively.

If the density of the cylindrical load is w gm. per cu. cm., computation of the maximum shearing stresses at points throughout the crust shows that the greatest shearing stresses occur on the lower surface of the crust directly below the centre of the load and are of magnitude in excess of $3w$ per sq. cm. Along the central line of symmetry, the shearing stress diminishes to $2w$ at three-quarter depth, continues to diminish, but eventually increases to become approximately $2.5w$ at the upper surface. Outward from the centre of symmetry, all these shearing stresses decrease until in the region below the edge of the load; then they increase for a while and subsequently diminish to zero for sufficiently large radial distances.

For example, along the lower surface of the crust the shearing forces are in excess of $3w$ within an area of radius 70 km., diminish to $1.1w$ at 180 km., increase to approximately $2w$ at 250 to 300 km. from the centre, and diminish as the radial distance increases further. At three-quarter depth down through the crust the maximum shearing stress is of magnitude approximately $2w$ on the axis of symmetry, 0.8 at 180 km., and follows a similar pattern to that on the lower surface. On the upper surface below the centre of the load the shear is approximately $2.4w$, in the neighbourhood of the edge of the load it is approximately $1.5w$, and at 400 km. from the centre has an approximate magnitude of $0.8w$.

For a crust with a shearing strength of granite, namely 200 kgm. per sq. cm., failure of the lower portion of the crust below the centre of the load will occur when the surface load per cu. cm. is in excess of $200/3 = 67$ kgm. If the load is a cylindrical ice-cap of density 0.9 gm. per cu. cm. such a load is attained by ice of thickness $(67/0.9)/100$ km., that is, approximately $\frac{3}{4}$ km. The surfaces of constant maximum shearing stress in this region are dome-shaped upward from the lower surface. Presumably attainment of the shearing strength stresses in this region gives rise to plastic flow in a dome-shaped region whose boundary extends outward and upward as the thickness of the ice increases.

Shear, and therefore presumably plastic flow, at the upper surface first commences under the centre of the ice-cap when the ice reaches a thickness of $200/(2.4 \times 0.9 \times 100)$ km., that is approximately 0.9 km.

The portion of the crust outside the perimeter of the cap first begins to shear when the thickness of the ice is $200/(2 \times 0.9 \times 100)$ km. = 1.1 km. This shear commences at the lower surface of the crust at 250–300 km. from the axis of symmetry. It appears that the

lines of constant maximum shearing stress in this region are much steeper than those near the centre and hence this shear is more likely to extend upward through the crust and give rise to the phenomena known as "downpunching" (Daly, 1934). However, the results indicate that downpunching is not likely to occur until after there has been some plastic flow below the centre of the ice-cap. Such flow would affect to some extent the stresses elsewhere; the modification of the downpunching stresses due to this plastic flow has not been considered.

The previous remarks have assumed that the stress pattern in the crust is due entirely to the surface load and have ignored stresses due to gravity, etc., that may be present prior to the addition of the load. Such stresses could be superposed upon those of this paper, but this has not been attempted because of the difficulty of estimating such stresses, which depend upon the previous history of that section of the crust. The conclusions of this paper concerning the thickness of the ice-cap apply whenever the previously existing stresses at any point have adjusted to become hydrostatic.

So far the effect of an ice-cap of increasing height has been considered, but the previous analysis may be applied equally well to an estimation of the stresses in the crust below an ice-cap whose height decreases due to melting. On the assumption of a hydrostatic state of stress in the crust prior to melting of the ice, a reduction of height of $\frac{3}{4}$ km. would be sufficient to produce plastic flow at the bottom of the crust below the centre of the cap, while a reduction of height of 1.1 km. would commence up-punching outside the perimeter.

Perhaps the most questionable assumption made in this paper is that of a density difference of 1 gm. per cu.cm. between the material of the crust and the supporting fluid. Some of the computed quantities, for example, the radial stresses, appear to be quite sensitive to changes in this density difference. Hence, it might be possible to relate the density difference to the observed displacement of the surface of the crust beyond the perimeter of the cap.

In conclusion it might be noted that, at any point in the crust, the radial displacement u_r is given by

$$u_r = (b/\mu) \int_0^\infty G(s, z) \, . \, q(s) \, . \, J_1(sr) \, . \, ds$$

where $G(s, z)$ has already appeared in the expressions for the stresses, b is half the thickness of the crust, and μ is one of the elastic constants of the material of the crust. Applied to the granite crust as postulated, $b = 20$ km., and $\mu = 2.8 \times 10^{11}$ c.g.s. units. For an ice-cap of thick-

ness 1 km., the outward radial displacements in metres at the upper and lower surfaces of the crust are as listed in the table below.

Radial distance (km.)	20	40	60	80	100	120	140	160	180	200	400
Upper surface	−11	−21	−31	−41	−50	−59	−67	−72	−75	−74	−25
Lower surface	12	23	34	44	54	64	72	78	81	80	

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVII : SERIES III : JUNE, 1953
SECTION FOUR

On the Formation of Pillow Lavas and Breccias*

J. F. HENDERSON, F.R.S.C.

Introduction

PILLOW lavas are widely distributed throughout the geologic column, but nowhere are they more abundant than in the Archaean greenstone belts of the Canadian Shield. The problem of how and why the pillows formed is a fascinating one and none of the many theories advanced seem entirely satisfactory in accounting for the structure.

During the past few years the writer has participated in the detailed mapping of the Yellowknife greenstone belt, Northwest Territories (Henderson and Brown, 1952), which is made up in large part of pillowed and non-pillowed flows and associated breccias. The belt is characterized by an abundance of clean, glaciated rock outcrops which give an unusually good opportunity for study. In particular, an island near the mouth of Yellowknife Bay offers an almost wholly exposed cross-section of more than 1000 feet of nearly vertical, pillowed flows and breccias. From the study of this and other sections the conclusion has been reached that the breccias and the pillow lavas formed in the same way and that the key to the origin of the pillows is to be found in the breccias. Support for this conclusion is found in the Quaternary and Recent pillowed lavas and breccias of Iceland which have been described by Noe-Nygaard (1940).

This paper describes the pillowed lavas and breccias of Yellowknife and compares them with those of Iceland. The conclusion is reached that pillow lavas are a type of breccia formed by extrusion and coagulation of the lava in water.

Ellipsoidal and True Pillow Structure

In his classic paper on the origin of pillow lavas Lewis (1914) has reviewed 98 descriptions of pillow and ellipsoidal structures. Of these, 32 suggest subaqueous origin and 52 imply subaerial origin and Lewis

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concludes "that neither the presence or absence of water, per se, can be predicated as particularly favourable to the formation of the structure." More recently Fuller (1931) has attributed the development of pillows in the Columbia River basalts to extrusion in water, but Hoffman (1933) from observations in the same general area reaches the opposite conclusion. Stearns (1937) from studies in Hawaii and Noe-Nygaard (1940) in Iceland conclude that pillows form only by extrusion of lava in water. On the other hand, Stark (1938) describes ellipsoidal structures in lavas of the Society Islands that formed subaerially.

As has been pointed out by McKinstry (1939), Macdonald (1953), and others, much of the disagreement on the origin of pillow structure is due to the vague usage of the term. Many geologists have applied the term to any ellipsoidal structure; yet several quite unrelated structures originating under entirely different conditions may appear ellipsoidal in certain sections. The writer follows McKinstry (1939) and Stearns (1937) in restricting the use of the term. As used in this paper, a "pillow lava" refers to a structure made up of spheroidal or ellipsoidal ball-like masses of lava coated with glass or its alteration product and detached from each other by fragmental glassy debris which also fills the interstices between the ball-like masses.

Somewhat similar ellipsoidal structures are commonly developed in pahoehoe flows. They are, however, quite unrelated in form or origin to true pillow structure, although the two are commonly confused. Such ellipsoidal structures are formed by lava tubes which are the characteristic internal structure of pahoehoe flows. An excellent description of how such ellipsoidal structures form and how they differ from true pillow lava is given by Gordon A. Macdonald (1953, pp. 172–4).

> Each large tube divides into smaller ones, each of which feeds a lobe of lava at the moving flow front. The entire front advances by successive protrusion of one small bulbous toe after another. Most toes advance only a few feet before they chill to immobility, after which the skin of the flow front ruptures at some other point and another toe is sent out . . . . The front is gradually built up by the accumulation of a heap of these toes, generally one to three feet in diameter, lying alongside and on top of each other. . . . A heap of pahoehoe toes belonging to several successive flows may appear in transverse cross section somewhat like pillow lava. . . . It does not, however, have the same genetical interpretation, and its misinterpretation may lead to erroneous deductions regarding the geologic history of the area. If they are well exposed, true pillow lavas can generally be distinguished without difficulty from pahoehoe toes. In general cross section

> each pillow gives an impression of radial structure, whereas each toe gives an impression of concentric structure. When the toes are exposed in three dimensions it can be seen that they are much more elongate than pillows. The major axis of a pillow is seldom more than 3 to 4 times as long as the short axes; a pahoehoe toe may exhibit a length along the principal axis of flowage several times greater than its cross sectional dimensions.

There is thus an important distinction betwee ellipsoidal structures formed by feeder tubes such as occur in pahoehoe flows, and true pillow lava which is made up of ball-like masses of lava. The reader will recognize that by far the greater part of the ellipsoidal structure of Archaean flows is formed by true pillows. The typical Archaean pillow lavas are not pahoehoe flows; they are not formed by a process of bulbous budding.

Pillow Lavas and Breccias of the Yellowknife Greenstone Belt

The pillowed flows of the Yellowknife greenstone belt are similar to those of other Archaean greenstone belts in the Canadian Shield. Such flows are so well known and have been described so frequently that only a brief description need be given here.

The typical flows are fine-grained, green to grey-green rocks that weather olive green. They were probably of original andesitic to basaltic composition, but are now altered to secondary minerals and are composed of 60 to 70 per cent hornblende and chlorite and 30 to 40 per cent altered plagioclase and epidote. Although dipping steeply, most of the flows are otherwise undeformed and the original volcanic structures are almost perfectly preserved. About 40 per cent of the flows are massive; the remainder have well-developed pillow structure.

A noteworthy feature brought out by detailed mapping is the great distance over which relatively thin flows and associated tuff beds can be traced. Thus in the Yellowknife belt the Stock variolitic flow, with a thickness of only 50 to 100 feet over the greater part of its length, has been traced for more than four miles along strike (Henderson and Brown, 1952). Several characteristic beds of cherty tuff, although only 25 to 50 feet thick, have also been traced for several miles.

The pillows (Fig. 1) of the pillowed flows range from a few inches to 5 feet or more in length but the averge is 1 to 2 feet. Each pillow has a ½- to 1-inch fine-grained dark brown to green rim with a massive, slightly coarser grained centre. Each pillow is separated from its neighbours by this rim and in no case has the writer observed a connection, or neck, joining two pillows; each pillow is thus an entity.

The large pillows may be bun- or mattress-shaped as compared with the nearly spherical shapes of the smaller ones. In the larger pillows, and to a lesser degree in the smaller ones, the undersides conform with the smoothly rounded upper surfaces of the pillows below; thus the bottom of a pillow is commonly a downward pointing cusp between the curved upper surfaces of the underlying pillows. As first recognized by Wilson (1911), the shapes of the pillows can thus be used to determine the direction in which steeply inclined flows face or top. Amygdules are commonly developed around the rims of the pillows with a slight tendency for a greater concentration along the upper edge.

FIGURE 1. Typical pillow lava, Yellowknife, N.W.T. Top of flow faces toward upper left.

These features indicate clearly that: (1) Each pillow is a distinct entity which is physically unconnected with its neighbours. (2) Because the bottom of each pillow conforms in shape with the top of the underlying pillow, it follows that each pillow was deposited subsequently to the pillows on which it rests. (3) Because the pillows are thus moulded on the ones below, they must have been deposited while still in a plastic condition. It seems reasonable to conclude

that the pillows were deposited one on top of the other as globules of lava with tough but flexible glassy skins and with still plastic interiors.

Further evidence on the origin of the pillows is found in the breccias so commonly developed at the tops and bottoms of flows. A particularly fine assemblage of flows and breccias is exposed on a small island near the mouth of Yellowknife Bay (Fig. 2). It should be emphasized, however, that these breccias are no different from

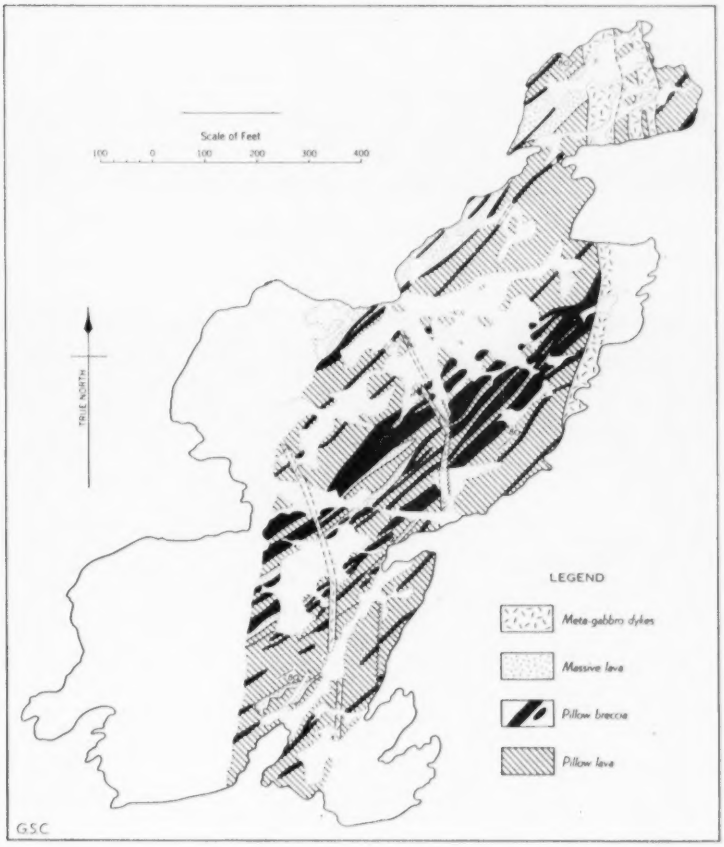

FIGURE 2. Distribution of pillow lava and breccia on island near mouth of Yellowknife Bay, Great Slave Lake, N.W.T.

FIGURE 3. Typical pillow breccia.

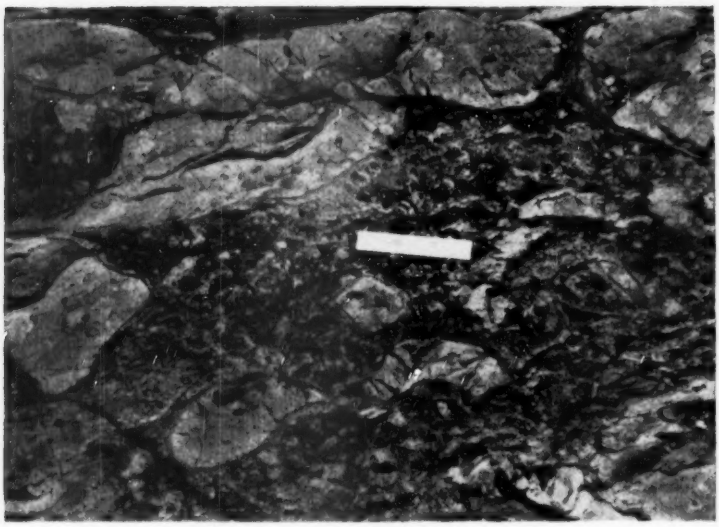

FIGURE 4. Contact of pillow breccia and overlying pillow lava.

those occurring throughout the belt; they are merely more abundant and better exposed. The breccia layers are anywhere from a foot or less to 100 feet thick. The flows and breccias strike northeast and dip and top 80 degrees southeast. The breccias (Fig. 3) are made up of masses of lava ranging from an inch to a foot or more in size in a matrix of smaller angular fragments from minute to the size of peas. The larger masses scattered through this fine breccia have dark, fine-grained rims and are amygdaloidal around their margins. They are in most respects identical with the pillows of a normal pillow flow; they differ only in being somewhat smaller, more elongate, and not as perfectly ovoid in shape. Were they in contact with each other instead of lying in a fragmental matrix, no one would hesitate to call them pillows. It seems appropriate to call the breccia a pillow breccia.

The fine breccia in which the pillows are embedded is composed of unsorted fine-grained, light green, angular to jagged fragments that range in size from minute to one-half inch or more. Under the microscope the fragments are found to be composed of a fine mat of secondary chlorite, altered feldspar, and epidote, with carbonate filling the interstices between the fragments. The fragments were probably originally glass.

The transition from pillow lava to pillow breccia takes place rather abruptly with the breccia filling the interstices of the adjoining layer of pillows (Fig. 4) and with an occasional large pillow of the pillow layer completely surrounded by breccia. There is thus a transition from pillow breccia in which the pillows are surrounded or "floating" in breccia, to normal pillow lava in which the pillows are in direct contact with each other and the glassy interstitial breccia is at a minimum. Pillow breccia and pillow lava differ only in the proportion of breccia to pillows. Is it not reasonable to conclude that the two have a common origin and that pillow lava is a type of breccia?

Globular Basalts and Breccias of Iceland

The conclusion that pillow lava is a type of breccia was reached from field studies of the Yellowknife greenstone belt. But there, although the original structures are almost perfectly preserved, the rocks are ancient, altered flows that have been highly folded and are now nearly vertical. Conclusions as to their original character and composition can be made with some assurance, but a certain amount of inference is necessary. Further, there is no direct evidence as to whether the flows were extruded on land or in water, although the

remarkable continuity and consistent strike of thin flows and interbedded tuffs over several miles, and other indirect lines of evidence, suggest rather strongly that they are subaqueous.

It is of interest, therefore, to find that the fresh undisturbed Quaternary pillow lavas and breccias of Iceland show similar relations. Furthermore, because many of these flows are subglacial, it is possible to show that pillow structure forms only when the lava is extruded in the melt water of the overlying glacier.

Noe-Nygaard (1940), who has described the Icelandic flows, calls the pillow lavas and pillow breccias "globular basalts" and "basalt globe breccias." However, he considers the terms synonymous; there is no doubt that "globular basalt" and "basalt globe breccia" are true pillow lava and pillow breccia.

As at Yellowknife, there is a transition from globular basalt (pillow lava) to basalt globe breccia (pillow breccia). One such transition is described as follows (Noe-Nygaard, 1940, p. 13): "On following the globular basalt massif westwards it is found that the close packing of the globes does not continue; the farther we go from the central area,

FIGURE 5. Elongated basalt globes in basalt globe breccia, Iceland (photograph by Noe-Nygaard, 1940, Plate 4, Fig. 2).

we find an even greater admixture of brownish, glassy matrix between the individual globes. The rock this forms appears as a glassy breccia in which the isolated glass covered globes seem to float." (Fig. 5.)

Similar transitions from globular basalt to basalt globe breccia are described by Noe-Nygaard (1940, p. 58) and he concludes that his investigations "have established the presence of complete transitional forms between compact globular basalt and basalt globe breccia whereby their common origin is proved." Comparison is made between the subglacial flows and breccias with typical pillow structures and the subaerial flows formed in front of the ice front which entirely lack these structures. Convincing evidence is presented to show that extrusion in water (in this case melt water from the overlying glacier) is essential for the formation of pillow lava and pillow breccia.

Conclusions

In summary and conclusion it is suggested that:

1. Pillow lavas have a common origin with pillow breccias into which they grade.

2. From indirect evidence in our Archaean flows and from excellent direct evidence in the Quaternary Icelandic flows, extrusion in water seems essential for their development.

3. Pillow breccia and pillow lava are formed by the chilling action and great heat consumption of the water. The process is akin to the granulation of slag on entering water and an aggregate or breccia of glass fragments is formed. In nature, of course, it is on a much grander scale and globules of lava with glassy skins tend to form; these are the small "floating" pillows in the breccia. A slight change in conditions leads to the development of pillows exclusively, with little or no interfilling of glass breccia; these are our pillowed flows.

4. The pillows form as globules of lava with tough glassy skins and are transported as entities to their final place of deposition. In submarine eruptions the globules (pillows) would probably be given great mobility by the envelope of steam that must surround them; they would tend to spread out over large areas on the sea floor. This may explain the great lateral extent of relatively thin pillowed flows commonly observed in Archaean greenstone belts.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA

VOLUME XLVII : SERIES III : JUNE, 1953

SECTION FOUR

Some Aspects of the Cooling of the Earth

J. A. JACOBS

Presented by J. T. WILSON, F.R.S.C.

OF all the problems concerned with the constitution of the Earth's interior, the ones which offer the greatest challenge today are those connected with its thermal properties. From a detailed analysis of seismic waves, Jeffreys, Gutenberg, and Bullen have determined the variation with increasing depth of density, pressure and the elastic constants. The results of their work, which has extended over many years, are generally accepted today, and it does not seem likely that there will be any radical changes in their values in the future. On the other hand, values of the temperature, thermal coefficient of expansion, thermal conductivity, etc., have in the past only been extrapolated from laboratory data, and extreme doubt and uncertainty must exist when these extrapolations are extended to the enormous pressures that prevail in the interior of the Earth. It seems preferable, therefore, to make use of seismic data interpreted in the light of the theory of the solid state to obtain additional information on the behaviour of these physical quantities with increasing depth. This method has already been used to great advantage by Verhoogen, Birch, Uffen, and Jacobs.

The older idea that the Earth's core consists of iron has been challenged in recent years. Thus Kuhn and Rittman in 1941 suggested that the whole of the interior of the Earth consisted of undifferentiated solar matter whose main constituent is hydrogen. This hypothesis however raises many difficulties and has invoked severe criticism in many quarters (see, for example, Elsasser, 1950a). More recently, Ramsey (1948, 1949) has put forward the hypothesis that the Earth consists of a homogeneous material having essentially the composition of the mantle, i.e. of a simple magnesium iron silicate such as olivine. The boundary between the core and mantle is regarded as a phase change in the material, the material in the core being a metallic phase of the silicates. It is unwise to be dogmatic, but it now seems more likely that Ramsey's hypothesis is not true. Ramsey originally put forward his hypothesis in an attempt to reconcile the densities

of the inner planets with the present views on the origin of the solar system. However, the latest values of the masses of Mercury and Venus do not support his theory (Kuiper, 1952). Quite apart from these failings in the field of astronomy, Elsasser (1950a, 1951) has shown that Ramsey's hypothesis does not agree with data on the Earth as viewed from the standpoint of theoretical physics. Since none of these new ideas on the constitution of the Earth's core is as satisfactory as the older views, it will be assumed that the Earth's core consists of an iron nickel alloy similar to that found in iron meteorites. With this model of the Earth, three problems will be considered.

The Inner Core

An analysis of all seismic records shows that no transverse waves have ever been observed to pass through the Earth's core, from which it is deduced that at least part of the core must be liquid. It has been suggested, however, that the core contains an inner core beginning at a depth of approximately 5,000 km. which is solid, although no proof of this has ever been given. In support of this hypothesis Bullen (1947) has shown that the rise in velocity of longitudinal waves at this depth can be accounted for by assuming the inner core to be solid but of the same composition as the rest of the core. In a recent and detailed study of the constitution of the Earth's interior, Birch (1952) concludes that the inner core most probably consists of crystalline iron, and the outer part of liquid iron.

Most theories of the origin of the Earth[1] agree that it passed through a molten stage before finally separating into the different layers, but no physical explanation has been given as to how in such a case an inner core could have become solid. The work of Uffen (1952), which is based on seismic data and the theory of solids, indicates that the melting point gradient in the mantle is considerably less than the theoretical curve proposed by Jeffreys (1952). At the boundary between the core and the mantle, there will be a discontinuity, the melting point in the iron core being less than that in the silicate mantle. The melting point curve is thus likely to be of the general shape shown in the figure. As the Earth cooled from its molten state, the temperature gradient would be essentially the adiabatic, there being strong convection currents and rapid surface cooling. Solidification would begin at that depth at which the curve representing the

[1]Both Hoyle (1946) and Urry (1949) have shown that even if the Earth was formed from the cold accretion of dust particles, it would melt by the accumulation of heat from radioactive elements and thus become liquid, before subsequently solidifying as the amount of radioactive material decreased with increasing time.

adiabatic temperature first intersected the curve representing the melting point temperature. It is suggested, therefore, that solidification began, not at the boundary of the core and mantle as is at present supposed, but at the centre of the Earth. A solid inner core would continue to grow until a curve representing the adiabatic temperature intersected the melting point curve twice, once at A, the boundary between the core and mantle, and again at B, as shown in the figure.

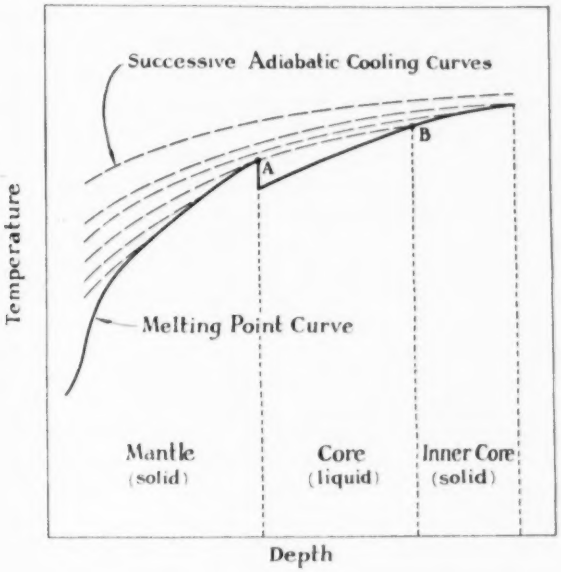

FIGURE 1

As the Earth cooled still further, the mantle would begin to solidify from the bottom upwards, trapping a liquid layer between A and B. The mantle would cool at a relatively rapid rate leaving this liquid layer effectively insulated above by the rapidly thickening shell of silicates and below by the already solid iron inner core.

In the above argument, no specific values of temperature are postulated and the precise behaviour of both the melting point and adiabatic curves is immaterial. If these curves vary qualitatively as shown, then a physical explanation for the existence of a solid inner core has been established.

Convection Currents in the Earth's Core

The geomagnetic secular variation can be interpreted as the result of motions in the fluid core and Elsasser (1950b) has shown that thermal convection provides the only satisfactory mechanism for the generation of such motions. The conductive heat flow Q is obtained from the product of the conductivity k and the temperature gradient τ. Following Bullard (1950) and Elsasser (1950b), the value of k in the liquid iron core is taken as 0.18 cal/cm. sec. deg. Since the core is in a state of convective agitation, the temperature gradient will be the adiabatic, an estimate of which has recently been made by Jacobs (1953). At the boundary of the inner core (i.e., at a depth of approximately 5,000 km.), he obtained a value of 0.10 deg./km. for τ. Thus the conductive heat flow Q at the boundary of the inner core is 1.8×10^{-7} cal/cm^2 sec. Thermal convection will be set up in the core if, owing to the physical conditions that prevail there, the transport of heat radially outwards exceeds the transport of heat by conduction alone. Thus if the heat supply at the boundary of the inner core is greater than 1.8×10^{-7} cal/cm^2 sec., the liquid core will become unstable and slow convection currents will be set up.

A large proportion of the heat flow through the Earth's crust is due to radioactivity so that the measured mean heat flow through the crust, viz. 1.3×10^{-6} cal/cm^2 sec. (Birch, 1942), is representative of the order of magnitude of the radioactive heat developed in the crust. This figure is about seven times the value of Q, but since the surface area of the inner core is only about 5 per cent of that of the crust, the radioactive content of the inner core need only be about 1 per cent of that in the crust.

If the heat flow 1.8×10^{-7} cal/cm^2 sec. at the boundary of the inner core is generated in the inner core, the generation per gram of material is 0.35×10^{-15} cal/sec g. Paneth's (1942) results for iron meteorites give a heat generation of about 0.40×10^{-15} cal/sec g. Thus a core composed of iron meteorites similar to Paneth's would suffice to initiate convection currents. Bullard (1950) carried out similar calculations and found that a core composed of iron meteorites would fall short of the heat generation necessary by a factor of 4. This discrepancy is removed by using the above results of Jacobs for the temperature gradient.

Thus the geomagnetic secular variation can be accounted for by convection currents in the fluid core, which can be set up by the radioactivity of an inner core composed of material similar to that of iron meteorites.

Transfer of Heat from the Core

At the boundary between the core and mantle, the adiabatic temperature gradient is 0.30 deg/km (Jacobs, 1953), so that, taking, as before, the conductivity of the liquid iron core to be 0.18 cal/cm sec. deg., the conductive heat flow at a point just inside the core is 5.4×10^{-7} cal/cm^2 sec. At a point just inside the mantle, the temperature gradient is not likely to be very different from the melting point gradient. Little is known about the melting point and conductivity of the silicates which compose the mangle at the extreme pressures that exist at depth. Rather than make dubious extrapolations from laboratory data, the recent values of Uffen (1952), which are based on seismic data and the theory of solids, are used. His values of the melting point gradient and conductivity are 0.80 deg/km and 6×10^{-2} cal/cm sec. deg., respectively, so that the conductive heat flow is 4.8×10^{-7} cal/cm^2 sec. Thus about 90 per cent of the heat flow in the core at the boundary between the core and mantle can be carried away by conduction.

A word of warning must be given about any results which give definite numerical values of physical quantities at depth within the Earth. Owing to the complexity of the problem—particularly the thermal problem—any figures to be of any real value must be accompanied by a comprehensive statement of the assumptions that underlie them, and, if possible, an estimate of the probable errors. In the first part of this paper no numerical results are used in the argument, whilst the assumptions and probable errors in the values used in the last two sections have been discussed elsewhere (Jacobs, 1953).

The slight difference in conductive heat flows on opposite sides of the boundary between the core and mantle is not significant since the theory does not warrant giving numerical results to within 10 per cent. What can be said is that the conductive heat flows are of the same order of magnitude, so that sufficient heat can be removed from the core by conduction alone. This result has not hitherto been thought possible.

Support for the convection theory of orogenesis has often been claimed on the grounds that convection currents in the core are the simplest mechanism that will explain the Earth's magnetic field, and convection in the core will induce convection in the mantle. The result obtained in the last section of this paper is negative in that it does not establish that convection in the mantle does not exist, but it does show that convection in the mantle is not necessary in order to have convection in the core. It thus adds considerable weight

to the contraction theory of orogenesis, first proposed by Davison, Darwin, and Jeffreys and more recently examined by Scheidegger and Wilson (1950, 1952).

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVII : SERIES III : JUNE, 1953
SECTION FOUR

The Structural History of the Porcupine Gold Area, Ontario

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GEOLOGISTS have found from long experience that the geological structure of most mining camps appears to grow much more complex as mining operations proceed and knowledge of the camp increases. This has been particularly true of the Porcupine Area. The areal geological map accompanying the last report by Burrows (1924) shows only one fault and that a questionable one. Incidentally, this is the last report issued by a government department on this, the greatest of Canada's gold fields. Burrows' report was issued nearly fifteen years after the discovery of gold and the beginning of mining in Porcupine.

Important contributions have been made to our knowledge of the structure of this camp by: Graton, McKinstry *et al.* on the Hollinger mine (1933); Dougherty on the Vipond (1934); Langford on the McIntyre (1938); Hurst (1936 and 1942); Dunbar (1948, pp. 442–56); and a number of other geologists. The Ontario Department of Mines has done much geological work in the Area since 1930. Hurst has issued three editions of his valuable areal geology map (No. 47a, 3rd ed., 1939), but no report accompanies it. This map shows a great advance over Burrows' map with the addition of some formations not previously mapped and a number of major faults. Mining operations have disclosed the existence of many faults of considerable magnitude and almost countless minor faults, especially in the eastern part of the Area.

There has existed since the early days of Porcupine a great diversity of opinion among the geologists engaged there on many structural and stratigraphic features. It was hoped by a number of them that a restudy of the geology of the area as a whole and of the geology of a number of the mines might reconcile some of the conflicting opinions and throw new light on a number of problems. The author of this paper was therefore requested by the Manager of McIntyre Porcupine Mines Limited to make this study. Field and laboratory work was begun in the summer of 1949 and continued for over two years. A new areal geology map on a scale of one inch equals 1000 feet was prepared

and this large map made it possible to depict many features that could not be shown on maps of much smaller scale. The writer is greatly indebted to Dr. Balmer Neilly, President of McIntyre, for permission to present this paper. Later a period of three months as consulting geologist with Hollinger Consolidated Gold Mines Limited added greatly to the author's knowledge of the geology of the camp and gave an opportunity to test conclusions previously reached when engaged at McIntyre. The geologists and officials of the mines showed great courtesy in furnishing advice and information while the work was in progress and to them sincere thanks are expressed for all their aid. Thanks are also due Professor S. E. Wolfe of the University of Toronto who rendered valuable assistance in the field work during two summers.

Stratigraphy

The following series and systems of rocks are represented in Porcupine: Pleistocene; Keweenawan; Matachewan; Algoman; Haileyburian; Timiskaming; and Keewatin. A brief description of each division is essential to an understanding of the events that transpired in the development of the structural features found there today.

The Pleistocene rocks consist of the common drift, and alluvium and lacustrine deposits. The Keweenawan is represented by olivine diabase dikes and this rock, as in so many other areas in the Canadian Shield, is the youngest of the Precambrian rocks. The dikes are, as a rule, larger than the older Matachewan dikes, but so far as can be seen, they came in with little or no crustal disturbance. There is one feature of their occurrence for which no satisfactory explanation is offered and that is the fact that north of the Porcupine Creek fault they run generally northwest-southeast, and south of the fault, nearly east-west. The Matachewan comprises quartz disbase and gabbro, the former mainly porphyritic with altered plagioclase phenocrysts. This rock, like the olivine diabase, seems to have been injected without appreciable folding or faulting. The dikes trend in a general northwest-southeast direction and they are numerous as many have been encountered in drilling and mining where they are not exposed on the surface.

The Algoman

The Algoman was, in many respects, the most notable period of the Area's geological history. The rocks of this system are all igneous and intrusive: soda-granite; quartz diorite; alaskite; quartz and feldspar porphyries; felsite; and albitite. The gold deposits are gene-

tically related to the Algoman magma. The area is remarkable in that all the above rocks are highly sodic with almost complete exclusion of potash except for a subnormal quantity in the granite and a late injection of potash solutions just preceding and accompanying the formation of the gold deposits.

The greatest crustal disturbances in the Porcupine Area occurred during the Algoman with extensive folding and faulting.

Haileyburian

The Haileyburian epoch is represented by a group of basic to ultrabasic intrusions, mostly peridotite and some dunite. Commercial asbestos has been quarried from these rocks in two places. These rocks are most abundant in a zone along the Porcupine Creek fault and it may have influenced, to some extent, their occurrence. Since such rocks were readily sheared they gave rise to great quantities of serpentine-talc-chlorite schists and lubricated the fault zone. There is no evidence that folding was concerned with their injection.

Timiskaming

The Timiskaming series consists of pyroclastics and sediments which occupy a large section of the important Porcupine syncline. No lava flows have been found in the series. There is, at many places, a graphitic slate on the bottom of the Timiskaming, overlying an eroded surface on the Keewatin lavas. Above this slate lies the Krist fragmental, a pyroclastic consisting mainly of fragments of acidic porphyries like the later Algoman intrusive porphyries. In addition to the porphyry fragments there are those of Keewatin lavas, slate, quartz, and chert. Some of the boulders of Keewatin greenstone are over three feet in diameter. This formation grades gradually into conglomerate and it supplied most of the materials in that rock. It has been found that the majority of the boulders formerly called granite are not granite, but porphyry like the Algoman porphyry. The Krist fragmental was long considered intrusive porphyry and was so mapped by Burrows. Large sums of money were spent in drilling around masses of it in the mistaken idea that it was porphyry which has long been known to be associated with the gold deposits. It is, however, the most barren formation in the Area.

The explosive volcanic activity which produced the Krist fragmental was unaccompanied by folding or faulting.

The Timiskaming conglomerate, in places, occupies the position of a basal conglomerate lying on the Keewatin lavas, but lenses of this rock may be found scattered throughout the series in greywacke,

quartzite, and slate, the other rocks of the series. This feature considered along with the association of banded, varve-like slates has suggested to some geologists that there was glaciation in the Timiskaming.

Hurst (Map 47a) divided the formations described above into a lower Hoyle, and an upper Timiskaming series separated by an important unconformity. This division is not accepted by the author because this "unconformity" is regarded as a section of a large fault, the Gold Centre fault described later in this paper. Further, the rocks of the Hoyle and Timiskaming are so similar that they cannot be distinguished from one another in many places and they both have similar relations to the underlying Keewatin lavas. The situation will be discussed further when dealing with folding and faulting. The sediments were greatly folded and faulted during the Algoman revolution.

Keewatin

The Keewatin rocks show a great development in this area. One measured section on the north side of the Porcupine syncline contains over 15,000 feet of lava with the flows all facing southward and dipping from vertical to steeply northward. The total thickness of lava flows and thin beds of sediments and pyroclastics interbedded with them is doubtless much greater than the figure mentioned. The Keewatin presents several interesting problems and some of the major structural features in Porcupine appear to have had their inception in this period. The great difference in the formations on the opposite sides of the Porcupine Creek fault supplies one problem and the existence of the Porcupine syncline on the north side of this great fault another one. There must have been marked differences in the physiography north and south of this fault even back in the Keewatin period. Such differences influenced the development of major structural features up to the close of the Algoman.

The Keewatin on the north side of the Porcupine Creek fault consists almost entirely of lava flows, basic to intermediate in composition: dacite, andesite, and minor basalt. There are thin beds of sediments and pyroclastics between some lava flows. The thickness and lateral extent of some of these flows suggest fissure eruptions, but the frequent occurrence of sediments and pyroclastics indicates craters and explosive volcanism. Pillows are abundant and many of them well developed, and this feature combined with the occurrence of sedimentation indicates deposition under water, and a basin in this section in Keewatin time.

Another prominent feature of the lavas in the section of the Area north of the Porcupine Creek fault is the presence of three major variolitic flows, and some minor ones. The most important one is known as the *spherulitic* flow and V-8 in the numerical nomenclature. It can be traced around the west end of the Porcupine syncline and it is a very important horizon marker. It is characterized by an abundance of variolites and its long narrow pillows, up to 17 feet in length. A second variolitic flow has been named the "chicken feed" flow (V-10B) because the variolites have suffered autobrecciation and a product resembling chicken grit has resulted. The pillows in this flow are smaller than those in V-8 and wider for their length. It is also a good horizon marker.

The author has recognized a third variolitic flow which has been numbered C-X because, although it is in the Central series of lavas, its exact position in this series is not quite certain. The existence of this third variolitic flow was at first doubted by a number of Porcupine geologists, but its presence has been so fully established on both sides of the Porcupine syncline by several geologists that doubt of its existence can no longer remain. The importance of the discovery of this new flow lies in the fact that it was formerly mapped as V-8 and this led to confusion in interpreting the structure in some parts of the camp. It is separated from V-8 by No. 99 andesite, a prominent flow in many parts of the area. The distinction of C-X from V-8 changes the large, complicated drag fold just east of the Coniaurum mine (see Map 47a) to a simple anticline plunging east and long recognized in this mine. This flow does not carry its variolitic and pillow structure as continuously along its strike as the two other variolitic flows, but it has wide occurrence and is also a valuable horizon marker in deciphering structure.

South of the Porcupine Creek fault there is a marked difference in the Keewatin. There are few good pillows; there are no prominent variolitic flows, and there are large areas of pyroclastics. There is a large amount of siliceous banded iron formation, which does not occur north of the fault. There is a zone of acid pyroclastics with a few rhyolite flows on the south side of the fault. These rocks are similar in composition to the Krist fragmental, but more altered and they contain much barren pyrite. The presence of these pyroclastics along the large fault zone suggests that it was to some extent responsible for releasing acidic rock from the extensive granite magma which had been developing under Porcupine. So far as can be determined, this explosive type of volcanism was not accompanied by folding.

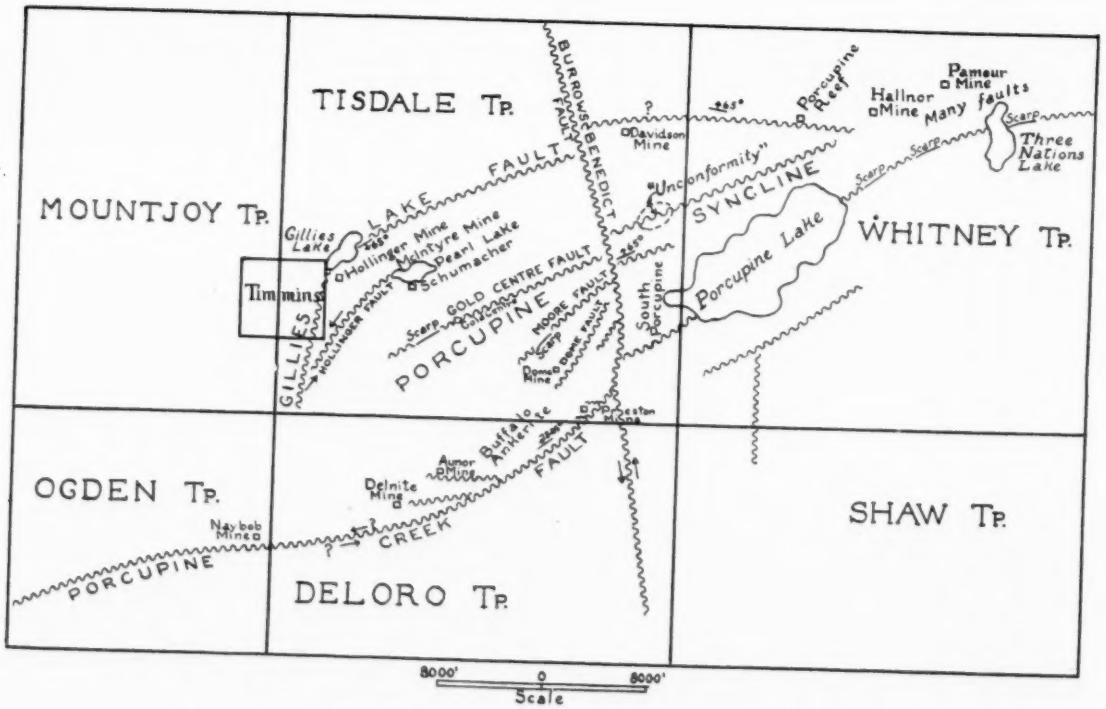
The structure south of the Porcupine Creek fault also differs much from that north of it. In the latter area there are long sweeping folds which can be delineated without much difficulty. In the southern area there are, especially in its eastern part, many domal structures with gentle dips and underlain by domes of granite. In the western part the folds are longer and tighter and trend in a general northeast-southwest direction, but they lack the regularity and continuity of those north of the great fault. Most of the granite in the Area is found south of the fault and many albitite dikes which very seldom appear above the 2000-foot levels in the mines north of the fault may be seen at the surface south of it.

The great differences in the conditions north and south of the fault lead to the conclusion that probably the rocks in the two areas were all formed at about the same time in the Keewatin period, but that there was a physiographic "high" south of the fault and a "low" north of it. The Porcupine Creek fault began to develop at an early stage and permanently separated these two areas from one another. The stage was thus set at a very early time for the development of the present structural situation in the Porcupine Area.

Structural Geology

Folding

There were at least two periods of extensive folding in Porcupine, one at the close of the Keewatin and the other during the Algoman. Much discussion has centred around the question as to whether there is an important unconformity between the Keewatin and Timiskaming, but its existence has been well established. Holmes reports a large unconformity under the sediments in the Dome mine and Bell one in the Hallnor on the north side of the Porcupine syncline. A study of logs of holes drilled some years ago on the Solidago property northeast of the Coniaurum mine has supplied some very interesting evidence regarding this matter. A series of holes running a little east of north in nearly a straight line across the strike of the Keewatin lavas for over 4000 feet penetrated the Timiskaming sediments and Krist fragmental and entered the lavas along the border of the basin. These logs made it possible to plot a profile on the surface of the lavas and this shows a remarkably regular surface of erosion (Fig. 1). There is one valley-like depression in this profile, but for most of it the gradient is less than 10 degrees. Since this line of holes crosses the general strike of the lavas it is evident that the lavas were highly folded and then reduced to a peneplain before the deposition of the Timiskaming. It would be impossible to have the situation



Sketch map of the Porcupine Gold Area showing the major faults.

that exists in this area if the Keewatin lavas were folded for the first time when the Timiskaming sediments were first folded.

So far as can be determined there was no important folding between the beginning of the Timiskaming and the Algoman period when very extensive folding occurred which was accompanied by the intrusion of granite and much porphyry. Major faulting preceded this folding.

It seems probable that some movement on the Porcupine Creek fault occurred during the folding at the close of the Keewatin, and

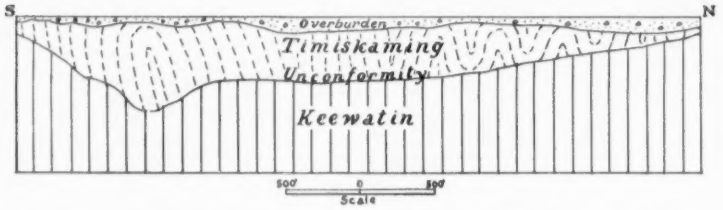


FIGURE 1. Section showing large unconformity between Keewatin and Timiskaming disclosed by drilling on Solidago property. Folding in Timiskaming sediments only diagrammatic.

that some porphyry magma escaped from the large granite magma beneath this area and rose part way to the surface without reaching it. This porphyry was blown out to form the Krist fragmental shortly after sedimentation began in the Timiskaming and this accounts for the similarity in composition of the fragments in the Krist fragmental and the intrusive porphyry which came up during the great Algoman disturbance. It is probable that the intrusive porphyry occupied the crater or craters from which the Krist fragmental was ejected.

The Porcupine syncline was formed by thrusting from northwest and southeast quadrants. The lavas on the north side of it face southward and dip from vertical to steeply northward. Near the Dome mine there is some overturning of these rocks toward the northwest and thrust faulting in the same direction. The syncline is very narrow in the eastern section where it is overturned to the south and where the south limb has been mostly removed by faulting and erosion. The strong compression of the syncline in this section was due to the presence of large granitic masses on the south and rather massive and strong bodies of lava on the north squeezing the sediments like a vise. This strong compression of the eastern end of the syncline in the Porcupine Area caused a considerable amount of movement of the formations westward and upward. Evidence of this movement is found in the slaty cleavage in all the finer-grained sediments of the

Timiskaming and in the attitude of the numerous small drag folds in the area. It appears to have been an important factor in the development of the extraordinary pitch of the basin at 45 to 50 degrees east. This pitch is evident in all the structures in the syncline, such as the pillows, fluting, slickensides on small slips, and the porphyry intrusions. One can follow some of the porphyry intrusions for thousands of feet and their eastward pitch does not vary over 5 degrees. This pitch in the formations is not found south of the Porcupine Creek fault nor west of the Gillies Lake fault. All the important mines in Porcupine lie within the area in which it prevails. The porphyry intrusions followed the pitch upward and westward. The cross-folding south of the Hollinger mine appears to be related to the squeeze of the rocks westward where the north-south and east-west forces operated at cross-purposes. The Crown porphyry breccia was a result of this condition. It is a large body of brecciated Keewatin which appears to have originated just previous to, or contemporaneously with, the injection of the Crown porphyry which intruded it as dikelets.

As previously stated, the large drag fold east of the Coniaurum mine on Map 47a is replaced by a simple anticline pitching east. This anticline has been recognized in the Coniaurum mine for many years, but owing to the confusion resulting from the variolitic flow C-X being mistaken for V-8, the structure east of the mine was not correctly interpreted.

Faulting

The major faults in Porcupine are outlined on the accompanying sketch map. Some of them are large of size and there was more than one period in which major faulting occurred. It has been shown that the Porcupine Creek fault had its inception as far back as the Keewatin. Most of the large faults have a general northeast strike roughly parallel to the folded structures, but there are a few north-south cross faults which are younger than the former. They offset the northeast-trending faults and their age has not been definitely determined; they may be a little or much younger. The Burrows-Benedict fault is the largest and most important of these. The northeast faults show, in many places, much carbonatization, an effect which preceded gold deposition by a short period. The north-south faults lack this feature.

Porcupine Creek fault. This is the largest fault and shear zone in this district. It is a break of great magnitude as it can be traced for at least 80 miles from a point west of Ogden township eastward to Harker only about 10 miles from the Quebec boundary. It is probably much longer than that, but west of Ogden township its course is

concealed by overburden, as it is at a number of other places. It is believed that this fault originated in the Keewatin period and that there has been movement on it during several stages in its history, the greatest being during the Algoman revolution. Large bodies of Haileyburian ultrabasic rock were sheared into serpentine-talc-chlorite schists at that time and there were minor movements after the intrusion of the Algoman porphyries. Small bodies of porphyry intruded the fault zone and some of these show some fracturing and shearing similar to that which may be observed in the porphyries in many parts of the district.

There are serpentine-talc-chlorite schist bands in the Aunor and Delnite mines which are considered as branches of the fault zone extending west from the Buffalo Ankerite mine.

The existence of this great fault is well established in Porcupine. A schist zone was drilled in Ogden township and a serpentine-chlorite zone served as southern barrier to the ore deposits at the Naybob mine. Here the zone was traversed by drilling and cross-cutting. South of the Paymaster and Preston East Dome mines the shear zone is 600–700 feet wide. This zone has been found by drilling under Porcupine Lake and a striking scarp may be seen on the road north from the highway to the Hallnor mine. Another scarp was found by drilling farther northeast and there is one on the east side of Three Nations Lake. Few concise data exist on the amount of displacement and its direction as the fault zone is mainly barren of gold and the nature of the ground makes mining difficult. Mining men therefore shy away from work in this zone. It has been impossible to match rocks on the opposite sides of the fault to determine the nature of the displacement. Any figures on the direction and angle of dip that are available indicate that it dips north at 75 to 85 degrees south of the Preston mine. Since the younger rocks, the Timiskaming, are on the hanging wall of the fault, the conditions indicate a normal fault. On the other hand, the width of the shear zone in some parts of the fault zone would seem to require strong thrusting to produce so much sheared rock. In a recent paper, Escher (1952) states that the Feldbiss normal fault along one side of a graben in the Limbourg district, in the Netherlands, has a breccia zone from 40 to 200 metres in width on a dip of 65 degrees towards the graben. Such brecciation might result from normal faulting, but to produce all the shearing found in the Porcupine Creek zone, compression must surely be required. The conclusion one reaches is that most of the displacement was linear. As pointed out above, there is much evidence that movement on a large scale towards the west in the Porcupine syncline was a common feature.

Hollinger fault. A large fault has been recognized and carefully studied in the Hollinger mine. It strikes northeast to nearly east and dips on the average about 67 degrees southward. It has a horizontal displacement from about 1000 feet to 1700 feet with the north side to the west. It has been followed down to the bottom of the Hollinger mine and still deeper as a fractured zone on the McIntyre. The nature of the fracture varies greatly from point to point as there may be a single fracture or a wide zone of fracturing. An albitite dike follows the fault in places on the lower levels of the Hollinger mine.

This fault originated before the intrusion of the porphyry since the Pearl Lake porphyry occupies the fault zone in the upper levels of the Hollinger and McIntyre mines without appreciable offset. A prong of the Pearl Lake porphyry extends out to the southwest from the main body along the fault. The fault dips out from beneath the porphyry in the lower levels of the mines. The Millerton porphyry cuts across the course of the fault and is not offset appreciably. There has, however, been some movement on the fault since the porphyries were intruded because they are sheared and fractured to a considerable degree where they cross the fault. Extensive fracturing of the rocks on both sides of this fault was a great factor in the production of the very wide ore zone in the Hollinger and McIntyre mines.

Gillies Lake fault. It has been established in underground work by Hollinger that an important fault exists beneath Gillies Lake. It dips 65 degrees southeast and is considered a thrust fault, although no definite evidence has been found to determine the direction of the displacement. This fault begins at least as far southwest as the Moneta property in the southwest corner of Tisdale township and in this vicinity it is apparently joined by the Hollinger fault. It is believed by the writer to be a major fault with a length possibly as great as ten miles and extending northeast and east to the Broulan mine.

Evidence of faulting was found when drilling a property 6000 feet north of the Coniaurum mine and there is an important fault on the Porcupine Reef property. There is heavy overburden in sand plain and swamp between these two points and a large swampy depression lies north of the old Davidson mine and extends east to the Porcupine Reef. Little definite evidence of faulting can be obtained from a long stretch of what is believed to be the course of the Gillies Lake fault. If this fault extends through the Porcupine Reef we have the anomalous situation that the main fault in this property dips north 65 degrees where as under Gillies Lake it dips at the same angle to the southeast. This condition could be caused by a torsional movement, and a glance at the geological map shows that east of the Davidson mine the

formations swing southward from the general northeast trend that prevails around Gillies Lake.

Gold Centre fault. This fault was named by the author from Gold Centre, a village in Tisdale township under which it lies. This is another large fault at least 6 miles long and probably longer. It is difficult to prove the existence of such a structure because so much of its length is covered with heavy overburden. The reasons for placing this fault on the map are: (1) a small, but distinct scarp may be seen 2500 feet south of the town of Schumacher where the scarp striking N. 65 degrees E. cuts across the schistosity striking N. 85 degrees W., and a hole drilled across the strike of this scarp showed a loss of 25 per cent of the core and much carbonatization; (2) a very sharply outlined depression, extending from Gold Centre towards this scarp, stands out prominently on the aerial photographs; (3) when driving a long crosscut from the 1000-foot level of the Coniaurum mine southward into the Central Porcupine claims it was reported that a very confused situation existed in the lavas where this fault should pass; (4) northeast of the last place mentioned there is a sharp-walled depression in the Krist fragmental and there is a marked difference in the size of the fragments on opposite sides of this depression. There are also several minor faults in this locality which suggest branch faults from a large one; (5) an outcrop in the east-central part of Tisdale township shows an "unconformity" on Map No. 47a and it is believed that this is the Gold Centre fault rather than an unconformity; and (6) drilling cut a soapstone band 2000 feet northwest from the northwest corner of Porcupine Lake, and this might well represent the course of this fault considering that the trend of the formations are nearly east in this locality.

In the outcrop mentioned as labelled with an unconformity, several drill holes were bored and a number were drilled southwest of it. These showed some brecciation and a very disturbed condition of the sediments. These features might be associated with an unconformity, but no evidence of weathering and oxidation was found. Such would be expected with an unconformity whereas the break is clear cut and there is a marked discordance in the strike of the sediments on the sides of the fracture.

Much attention has been paid to the Gold Centre fault because its existence determines whether there are two series of sediments, Hoyle and Timiskaming, in the Porcupine syncline. It does not seem possible for there to be these two series because the sediments in them are similar, but a more important feature is the occurrence of a graphitic slate overlain by the Krist fragmental at the base of both

of them. This condition exists on both sides of the Porcupine syncline in its western part and there is the same large unconformity between both of these series and the Keewatin lavas. It has been argued that a large depression was eroded in the Hoyle sediments and Timiskaming rocks were laid down in this depression. If this were the case there should be another unconformity near the south side of the syncline to match that already mentioned. No such unconformity has been found. The lowest sedimentary rocks on the south border of the basin are just like those along the north border below the "unconformity."

Moore fault. A new fault was discovered by the author and Professor Wolfe north of the Dome mine. It was tentatively named the North Dome fault because it crosses the property of that name. H. S. Robinson, Chief Geologist of McIntyre Porcupine Mines, has decreed that this is to be known as the Moore fault.

This is a fault of considerable length. It has a scarp 15 feet high at a point about 1500 feet north of the Dome mine (Fig. 2). It can be followed most of the way to a point on the highway just west of South Porcupine. Here it is shifted 1300 feet north on the east side of the Burrows-Benedict fault and it appeared in a drill hole and a crosscut. Within a short distance east of the cross fault its course is deeply covered and it is lost to sight. It may run under Porcupine Lake to connect with the Porcupine Creek fault.

It has not been possible to determine accurately the amount or direction of displacement on this fault. It dips 65 degrees north on the east side of the Burrows-Benedict fault, but the dip steepens to the west and it is nearly vertical at the scarp mentioned. The fault dies out to the west in schisted conglomerate. There is much quartz adjacent to the fault on the North Dome claims, where the Temiskaming Mining Company had a small gold mine in the early days of the Porcupine camp, and in the hill just west of South Porcupine (Fig. 3).

Other faults. Reference has already been made to the north-south cross faults which are younger than those described above. Their age has not been determined. The Burrows-Benedict is the largest and most important of these tear faults and it has a horizontal displacement of about 1300 feet with the east side moved north.

A very large number of faults, some of considerable magnitude and striking in various directions, have been found in mine workings, especially in the eastern part of the Porcupine camp. These faults are thrust and normal, pre-ore and post-ore. The normal type seems to be dominant in the post-ore group and thrust faults dominant in

FIGURE 2. Scarp on Moore fault.

FIGURE 3. Quartz along Moore fault just west of South Porcupine.

the pre-ore, but conditions vary greatly. It appears that the Porcupine Creek, the Gillies Lake, and the Gold Centre faults converge toward the narrow part of the Porcupine syncline at its eastern end and this partly explains the presence of hundreds of smaller faults in the mines in this locality.

Faulting played a very important role in fracturing the ground in preparation for the deposition of the gold-quartz veins which are dominantly fracture fillings contrasted with replacement veins of many other gold-bearing areas. Small movements fractured the quartz and other gangue minerals and permitted the gold access to them. It is generally recognized that where there was no minute fracturing of the gangue there is no gold, even though the fracturing may be on a microscopic scale.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVII : SERIES III : JUNE, 1953
SECTION FOUR

Concretion Conglomerate in the Charny Sandstone, Quebec

F. FITZ OSBORNE, F.R.S.C.

Introduction

LOGAN, in proposing the name "Quebec Group," considered it to be made up of two formations, the Levis below and the Sillery above. Later work indicated that the Sillery is but the downward extension of the Levis and, therefore, of Lower Ordovician age (Raymond, 1913).

More recently, Ulrich and Cooper (1938) concluded that *Obolella pretiosa* (Billings, 1862), the only abundant fossil from the Sillery formation, belongs to the genus *Botsfordia*, which is Lower Cambrian. Rasetti (1946) confirmed this conclusion and suggested that, in view of the fact that Sillery has been used for beds of Ordovician age, "Charny" be used for the beds known to be Lower Cambrian.

Charny Formation

The Charny formation is made up of three kinds of rock which are interbedded with one another. These are, in order of decreasing abundance: red shale; green sandstones; and grey, black, and green siltstones.

Sandstones

Sandstone is justified historically as a name for the coarser clastic rocks of the Charny formation. The rocks are grey or olive green, the colour being determined by the amount of water in them at the time of examination. Actually, the rocks are diverse: some beds or parts of beds are sandstone grade, and others are conglomerate grade or grit grade.

The sandstones are in beds that are pronouncedly lenticular, but the individual beds tend to be massive. Some of them are as thin as six inches, whereas others are more than forty feet thick. Within the beds, the sandstones are heterogeneous, that is, sorting is poor, and grains of diverse sizes are mingled, although many beds show a tendency to have more of the larger grains toward the bottom. The

heterogeneity is particularly apparent in the distribution of the common "white quartz pebbles as large as peas" (Logan 1863).

Besides the pebbles of quartz mentioned above, the sandstones contain angular to rounded grains of quartz and feldspar as well as diopside, augite, hypersthene, garnet, and epidote, and rarer minerals. The minerals are such as could be derived from a region of crystalline rocks like that north of Quebec city. Glauconite and collophane are moderately common, and small to large plaques of shale are abundant. The groundmass of the sandstones is composed of silt-grade particles similar to the coarser grains and a cement of chlorite and illite. In places, the matrix has been replaced by a mosaic of grains of carbonate, in which case the feldspar of the larger grains has been replaced to a greater or less extent by the carbonate.

The concretion conglomerate forms part of a bed of sandstone, and, therefore, the origin of the conglomerate must be related to the origin of the sandstones. The origin of the sandstones may be inferred from the relationships of the beds to one another and to nearby shales as well as from the internal characteristics of the rocks. The evidence, which is too voluminous to detail in this paper, leads to the conclusion that the sandstones formed by downslope mass movement of marine sediments, which were ultimately deposited with shales and siltstones.

Within the last two decades, subaqueous mass movement has been invoked repeatedly to explain certain peculiarities of structures and associations of sedimentary beds. Because the movement takes place under water, the mass of unconsolidated material absorbs water, and, as a result there are degrees of dilution from the landslip type, analogous to surface landslides (Kuenen, 1948), with but little water to some turbidity currents, such as have been recognized in lakes, which have little suspended solid (Russell *et al.*, 1951). Although they have not been actually observed in nature, it has been inferred that turbidity currents of high density have formed, and some sandstones were deposited from them. Certain Italian sandstones described by Kuenen and Migliorini (1950) are good examples. The Charny sandstones show many features in common with the Italian rocks; however, they differ in that the beds of Charny sandstone are lenticular and, although grading can be seen in most beds, the grading in many beds is far from good. It is a reasonable inference that the sediments of the Charny sandstone moved downslope and came to rest in a shorter distance than the sediments of the Italian rocks.

Concretion Conglomerate

Both sides of the St. Lawrence River near Quebec bridge are marked by ridges of sandstones of the Charny formation. The ridges have been

cut through to bring the road and railway to the level of the deck of the bridge, and excellent sections of the sandstones are exposed. Concretion conglomerate is found at two localities on the west side of the cut that forms the approach on the north or Quebec end of the bridge.

The northern exposure (Fig. 1) is the more easily examined than the southern, which is stratigraphically 85 feet above the northern and in an inaccessible part of the wall of the cut.

The northern exposure shows a bed made up of an olive-drab sandstone at the top with grit to fine conglomerate below. The lower beds contain fairly closely packed spheres (or ellipsoids), which are from one inch to a foot in diameter and are composed largely of medium-grained sandstones (Fig. 2). The spheres show a tendency to break free from the matrix on the blasted surface and then resemble a heap of cannon balls. The matrix of the conglomerate part of the bed is very poorly sorted sand and conglomerate grade material. Some angular blocks and slabs of medium-grained sandstone occur with the spheres, but are much less abundant than the spheres.

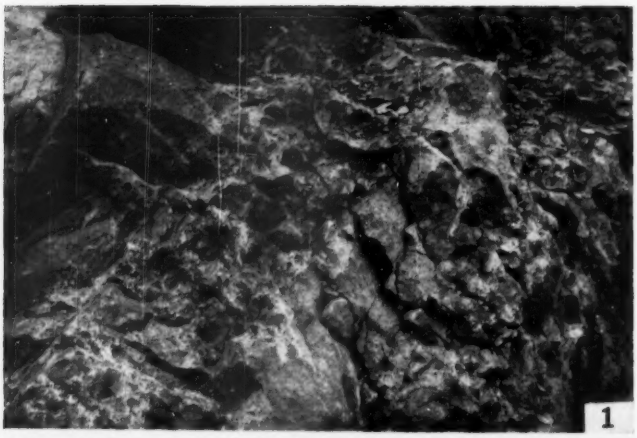
The conglomerate layer is explicable in terms of the origin of the sandstones as set forth above: during mass movement of the sediments, flow was turbulent, and the larger masses in the aggregate tended to sink towards the bottom of the moving mass. The water with the admixed material of finer sizes would, under conditions of hindered settling, allow the spheres to sink much more slowly than they would in water alone (Gaudin, 1939). Such an origin for the conglomerate is supported by the evidence afforded by large blocks at the base of other beds of sandstone, for example, one in a road-cut and quarry a mile south of the village of Charny.

The Spheres

The spheres (Fig. 3) are composed largely of a medium-grained sandstone, the grains of which are similar, except for size, to those in the Charny sandstones. A plaque, as much as three inches long, of black shale forms the nucleus of each sphere. The nucleus has its greater dimensions in the plane of the bedding of the sandstone of the concretion, and the sandstone is markedly better bedded than the typical Charny sandstone.

The spheres are cemented by carbonate which probably formed at the expense of an argillaceous cement. The cement of the matrix surrounding the sphere is, however, argillaceous.

The carbonate cement, the nuclei of shale, and the fact that bedding surfaces are apparent and cross each sphere suggest that the spheres



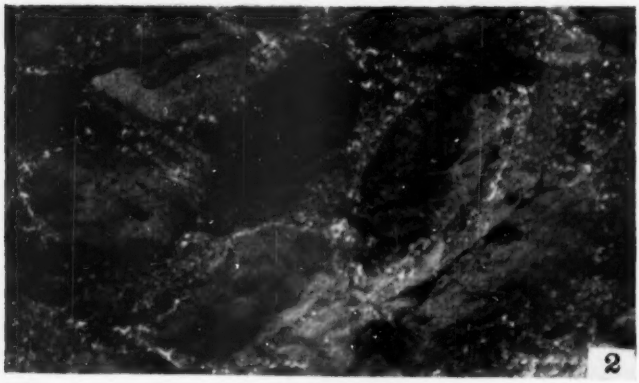


PLATE I.—Concretion conglomerate and concretions. FIGURE 1.—Concretion conglomerate, Quebec bridge approach; top of bed at upper left corner; broken and broken-out concretions towards base of bed. FIGURE 2.—Cross-sections of concretions and coarse matrix in which they are set. FIGURE 3.—Concretions; note shale nuclei in sandstone of sawed concretions and coarse matrix adhering to surface of unsawed spheres; pencil is 7 inches long.

are concretions which were released from sediments older than the Charny sandstones. The absence of snowball structures in the spheres shows that they cannot have been rolled in the manner of mud balls, and coalescent concretions giving dumb-bell shaped masses show that they cannot be the result of rounding of blocks of sandstone by wave action. The concretions were centres of local lithification in the otherwise unlithified rocks that slid from their original site of accumulation to form the present Charny beds.

In some Charny sandstones carbonate-cemented concretions comparable in size to those in the conglomerate occur. The concretions differ from those of the conglomerate in that they share the granularity and fabric of the surrounding rocks.

Interpretation

The sandstones of the concretions are important in interpreting the history of the Charny formation for they provide a sample of the older sediments which were poorly sorted with marked bedding and other indications of deposition in shallow marine water. The plaques of black shale that form the nuclei of the spheres are remnants of still older beds whose age cannot be determined. Obscure marks are possibly fossils, which would suggest a Cambrian age for the shale. It is probably mostly the broken-up material from these beds which gives the grains and masses of shale that are characteristic of most of the Charny sandstones.

It is unfortunate that the concretions do not give evidence of the cement in the original sandstones. Many beds of the Charny formation have concretions cemented by carbonate, but the cement has replaced an original argillaceous cement. The same is probably true of the sandstones of the concretions.

The conglomerate a mile south of Charny village throws additional light on the character of the beds that contributed sediments to the formation of the Charny sandstones. Some blocks of fine-grained, crossbedded marine sandstones are found there along with cobbles of conglomerate composed almost entirely of the "pea size quartz." It was probably the breaking-up of beds of the latter rock during mass movement that gave the "pea size quartz" in the Charny sandstones. Also at the same locality, the conglomerate has well-rounded cobbles of a fine-grained, dove grey, white-weathering limestone, which is similar in appearance to that of Lower Cambrian blocks from conglomerates in the Levis formation.

Conclusion

The concretion conglomerates give an insight into the Lower Cambrian stages of development in the Appalachian geosyncline. At that time, the wasting of a terrane similar to that of the Laurentian region north of Quebec was contributing debris to a geosyncline. Most of the debris was deposited in shallow marine water. Intermittently, the accumulated sediments, or some of them, travelled downward by mass movement to a part of the geosyncline which was below the level of effective wave action. The coarse sediments were there deposited with shales. Limestones of a foreland facies were also forming and apparently being uplifted so that they contributed some pebbles to a Charny conglomerate.

The deep zone in which the Charny sandstones were ultimately deposited was probably a precursor of the active zone along which the limestone conglomerates of Levis (Beekmantown) time developed in the siltstones of that formation.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVII : SERIES III : JUNE, 1953
SECTION FOUR

Problems of Precambrian Stratigraphy West of Sudbury, Ontario

JAS. E. THOMSON, F.R.S.C.

DURING the past four years the writer has had an opportunity to examine the geology in several localities along the north shore of Lake Huron between Sudbury and Sault Ste. Marie. This is the belt of Precambrian rocks that is shown on the Lake Huron sheet (Map 155A) of the Geological Survey of Canada as largely Huronian in age. Studies of this geological unit were commenced by Sir William Logan about a century ago and have been continued intermittently ever since, although little attention has been paid to most of this country in recent years. All of the investigations carried out by government surveys have been in the nature of reconnaissance surveys and a small part of the belt has never been mapped geologically.

The writer is convinced from preliminary examinations that more up-to-date geological surveys are necessary throughout the entire sedimentary belt from Sault Ste. Marie through Sudbury to Cobalt. The reasons are twofold, (1) to meet the requirements of modern mineral exploration, and (2) to acquire the factual geological information on which all sound deductions must be based. The writer has the greatest respect for the work of the pioneer geologists who toiled for so many years over the rugged country along the north shore of Lake Huron and eastward. Nevertheless, the geologists of today would be remiss in their responsibilities if they did not try to improve upon the work of an earlier generation.

As an experiment, a detailed geological survey was made by the writer in a small, strategically located area west of Sudbury in the summers of 1950 and 1951. The idea was to try out the methods now being used in the detailed studies of the main mining camps to see if they would reveal important geological information that had been unavoidably missed in reconnaissance surveys. This project has now been completed and the results have been published (Thomson, 1952).

The detailed study, combined with a brief examination of many places along the north shore of Lake Huron, has convinced the writer

that this whole Precambrian unit deserves systematic detailed mapping. It is envisaged that this would be a long-range project in which many geologists would participate. Such an undertaking involves adequate planning of all phases of the investigation. This paper deals with only one of the problems involved in a long-range project, namely the matter of tentative stratigraphy and correlation during the period of investigation. In this interim period ideas and conclusions will vary and fluctuate as new factual information is acquired. Are we to continually revise the old system of time and time-rock units, or introduce new terminology, or declare a moratorium on such matters until some reasonably sound basis of stratigraphy and correlation is attained? Geologists would undoubtedly disagree on an answer to these questions, and all would admit that there is no easy solution. The writer would advocate the cautious approach on the simplest and broadest basis, keeping in mind the requirements of the practical geologist, engineer, and prospector, who are interested in geology as a tool for the purposes of mineral exploration.

Stratigraphy in Baldwin Township

To illustrate some of the problems involved let me state our experience in the first detailed examination to be made along the north shore of Lake Huron by a government survey. The area selected for this study was the township of Baldwin located about 40 miles west of Sudbury and immediately north of the town of Espanola. Previous surveys (Collins, 1938), had indicated that it is a key area because of the variety of rock formations within its boundaries. Here are assembled rock groups assigned by Collins to the Keewatin and Sudbury series (pre-Huronian), and the Bruce series (Huronian), and also various types and ages of intrusives which are not being considered in this paper. A short distance to the south are rocks which Quirke (1917) placed in the Cobalt series. There is thus the complete stratigraphic sequence of the north shore of Lake Huron as established by the Geological Survey of Canada.

The stratigraphic succession as established by the recent survey of Baldwin township has been published (Thomson, 1952), and is shown diagrammatically in Fig. 1. This diagram is based on the detailed map (1952-1), but the bulk of the intrusives are deleted to simplify and emphasize the stratigraphy. Most of the intrusives are basic sills that are concordant with the strata and therefore do not greatly complicate the stratigraphic picture.

The major structural feature of the area is the Baldwin anticline. The core of the anticline is occupied by intrusives. The lowest strati-

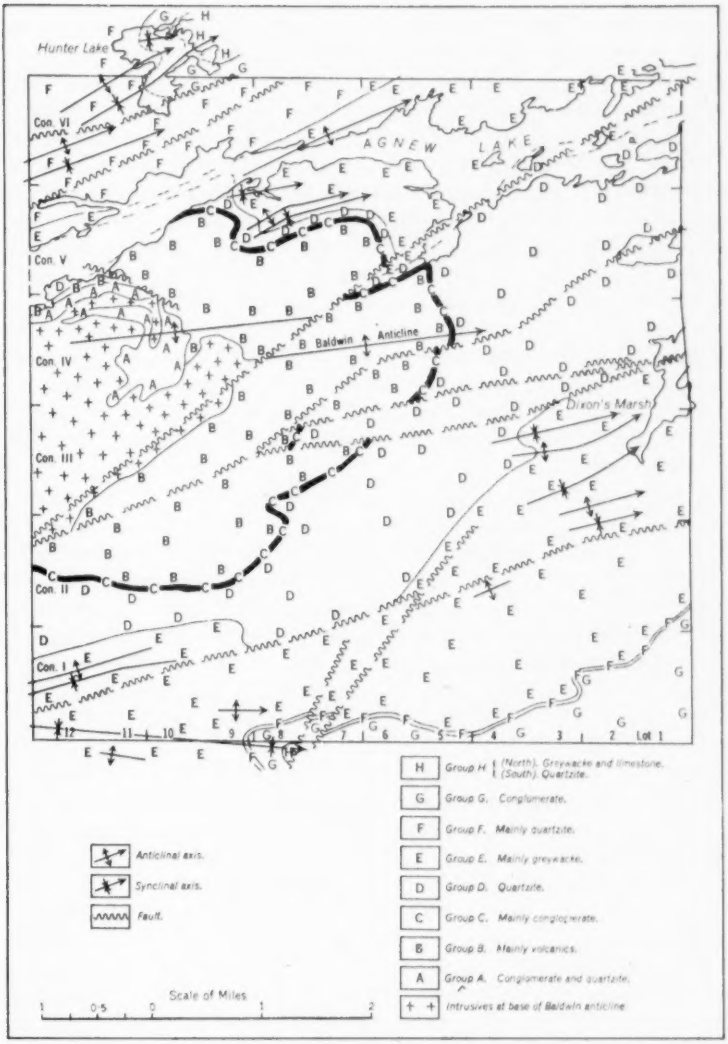

FIGURE 1. Generalized sketch map showing the stratigraphy of Baldwin township.

graphic unit is largely isolated in these and consists of conglomerate and quartzite (Group A in Fig. 1). This is overlain by a formation that is largely of volcanic origin but contains some interbedded sediments. This is one of the best marker horizons in the township. Lithologically, it resembles the so-called Keewatin volcanics in other parts of Northern Ontario, and was correlated with the Keewatin series by Collins (1938). The volcanic series passes by conformable transition into a quartzite (Group D). In the transition zone there are narrow bands of conglomerate (Group C) called Ramsay Lake by Collins. The quartzite, which Collins correlated with the Mississagi (Bruce series), passes upwards by transition into a unit that is predominantly greywacke (Group E). This was correlated with the McKim formation of the Sudbury series by Collins. Going southward the greywacke is overlain by quartzite (Group F) and conglomerate (Group G), which Collins correlated with the Mississagi and Ramsay Lake formations. Group H lies outside the township and was not studied in detail.

Table I shows how the stratigraphy established by the recent detailed survey compares with that given by Collins on the Espanola sheet (Map 291A). The problem of fitting Collins' time and time-rock units into the lower part of the newly established sequence becomes practically hopeless. If a correlation is made on the primary assumption that the volcanics of Group B are Keewatin, then, according to Collins' (1925) original definition of the Huronian, the overlying groups are pre-Huronian because they are not separated from the Keewatin by a great unconformity. On the other hand, in Collins' final (1937) résumé on the subject, he admits the occurrence of amygdaloidal lavas in the Mississagi quartzite. If the Mississagi is considered to be a mixed sedimentary-volcanic formation, the whole succession becomes Bruce series and the Keewatin would disappear. It is doubtful if Collins meant so drastic a change because he spoke of only "a slight vulcanism in or about Mississagi time."

The conclusions of the writer regarding the relation of Collins' Sudbury series to his Bruce series are in agreement with those of Burrows and Rickaby (1934, p. 13), Fairbairn (1941), and Cooke (1946, p. 33), in the Sudbury area. Even Collins (1925, p. 57), admitted that towards Sudbury there is little evidence of unconformity between the Bruce and Sudbury series. The added complication in Baldwin township lies in the fact that part of Collins' Ramsay Lake conglomerate and Mississagi quartzite underlie his Sudbury series. New names would have to be introduced for these and other units if Collins' stratigraphic terminology were to be continued.

TABLE I

COMPARISON OF STRATIGRAPHIC SUCCESSIONS

Map 1952-1, Ontario Department of Mines
Map 291A, Geological Survey of Canada

Stratigraphic succession[1]	Rock type	Relation to underlying unit	Corresponding formational name on map 291A	Stratigraphic succession
Top				
GROUP				HURONIAN (*Bruce series*)
H	*North*—Greywacke and Limestone	Transitional	Espanola (VI)	(VI) Espanola
	South—Quartzite		Mississagi (IV)	(V) Bruce
G	*North*—Boulder conglomerate	Transitional	Bruce (V)	(IV) Mississagi
	South—Pebble conglomerate		Ramsay Lake (III)	(III) Ramsay Lake
F	Mainly quartzite[2]	Transitional	Mississagi (IV)	
				PRE-HURONIAN (*Sudbury series*)
E	Mainly greywacke	Transitional	McKim (II)	(II) McKim
D	Quartzite	Transitional	Mississagi (IV)	
C	Mainly conglomerate	Transitional	Ramsay Lake (III)	
B	Mainly volcanics	Transitional	Keewatin (I)	(I) Keewatin
A	Conglomerate and quartzite	Unknown, cut by intrusives	Ramsay Lake (III) and Mississagi (IV)	
Base				

[1] See figure 1 for location and distribution of groups.
[2] Conglomerate at base on north side.

The writer examined sections of the Bruce series (Quirke, 1917) south of Baldwin township through the adjoining township of Merritt, although this was done only in reconnaissance fashion. Wherever seen, the strata faced south and dipped south at steep angles, but probably detailed examination would reveal areas of more complex folding. Near the south boundary of Merritt township the succession passes upwards into the Cobalt series, as mapped by Quirke. The writer found interbanding of the Bruce and Cobalt strata in perfect confor-

mity but did not follow the sequence far into the Cobalt series. He thus received the impression that the entire sedimentary sequence of the north shore of Lake Huron in the Espanola district is a closely folded unit similar in orogeny to the so-called Timiskaming series of other parts of northern Ontario. This is in general agreement with the earlier ideas of Coleman (1914, map facing p. 204), Miller and Knight (1913, table facing p. 126), Knight (1917, pp. 105–6), and Burrows and Rickaby (1934, pp. 12–13), in the Sudbury area. However, any stout defender of the Huronian might argue that this sedimentary succession is Huronian by definition because it has been traced eastward from the "original Huronian" at Bruce Mines. Until some working agreement is reached on such controversial points, and until additional detailed studies of the belt are completed, no definite conclusions on the regional correlation and orogeny are warranted.

Many questions regarding the fundamental principles of Precambrian stratigraphy are involved in a satisfactory solution of the problems raised here. Should the formational units with geographic names established by previous investigators be continued, with re-definitions, additions, and deletions where necessary? To date this is essentially what has been done, especially around Sudbury. Those who are familiar with this practice know how confusing it has become. If this method is continued throughout a long-range project each new survey along the belt will add to the confusion. The alternative is to discontinue all formational names until a sufficiently large area has been re-examined in detail. This is the method chosen by the writer for the recent studies in Baldwin township. In defence of this practice it may be said that for most practical purposes geographic names for stratigraphic units are unnecessary. This is especially true when the geographic name has various definitions. It is generally just as easy to describe a stratigraphic unit by its main lithological characteristics as it is to use a geographic name. In other words, a unit may be described as "quartzite" instead of "Mississagi quartzite." This is particularly helpful in the case of isolated outcrops where relationships are unknown. If all the structural data are shown on a map, the place of the lithological unit in the stratigraphic succession is indicated or it may be interpreted from structure sections or special stratigraphic diagrams. However, the practice adopted by the writer is contrary to the so-called "stratigraphic code" (Ashley *et al.*, 1933), and to the general practice of government surveys. It is true that the "stratigraphic code" generally avoids Precambrian problems, but it is widely used and is a generally accepted guide on stratigraphic principles and procedures. A return to the use of geographic names for

stratigraphic units may eventually be necessary in the "Huronian" district, if there is general agreement that it is desirable.

Principles of Precambrian Stratigraphy

In some parts of Canada the second century of geological surveys has been entered. The area under discussion comes in this category. Most of the reconnaissance or preliminary surveys have now been completed and the second stage, involving more detailed surveys, has begun. Is it not the time to review the principles of Precambrian stratigraphy to see if the reconnaissance methods upon which much of the succession has been built are going to be adequate for the new era of geological surveys? If they are not, this should be the time to throw off the shackles that bind us to an earlier tradition and may eventually hamper progress.

Lacking fossils, the earlier Precambrian stratigraphers used the next best criterion, which was lithology. Their stratigraphy was based primarily on lithology and secondarily on structure. In other words, the structural interpretation of highly folded areas resulted from the lithological correlation. Key sections were established in certain parts of the country and attempts were made to fit adjacent areas into the established stratigraphic column. This has sometimes been referred to as the "pigeon-hole" system because every rock formation had to be fitted into the standard classification. When this feat could not be performed a favourite trick has been to re-define the original definition to fit the facts of a particular case. Another scheme has been the creation of series, sometimes provisionally and without defining the limitations of the series in space and time.

This system had its advantages in the pioneering stages of geological surveys when a broad general correlation was all that could be hoped for. Sometimes its basis was so broad as to be all-inclusive. For example, the type locality of the Keewatin (Lawson, 1885), is an area of more than 3000 square miles on Lake of the Woods. It is largely covered by water but the outcrops show a great variety of volcanics and sediments. Similarly, anyone familiar with the original Huronian knows that a considerable part of it is farm land. In the light of modern knowledge some of these type localities are not a help but a hindrance. The attempt at correlation with the type locality is equivalent to the problem of a surveyor who tries to tie a survey, accurate to the nearest foot, to a base that is accurate to the nearest hundred feet.

In recent years the emphasis in highly folded Precambrian areas has changed from lithology to structure. In other words, the strati-

graphic sequence is the resultant, not the source, of the structural interpretation. Detailed mapping has shown that the stratigraphic sequence is effected by the lenticular nature of the original vulcanism or sedimentation, by strike faults, folding, and intrusion. These factors are often so variable that cross-sections drawn a mile apart may have little in common. Yet in reconnaissance surveys correlations may be carried for hundreds of miles largely on lithological evidence. It is thus only to be expected that confusion has arisen in applying the stratigraphy of reconnaissance surveys to detailed surveys. This confusion is cumulative and will continue to grow with each successive detailed survey. The most accurate stratigraphy is established where the best sections are exposed and studied, and where the largest amount of mining exploration has been carried on. It thus becomes rather absurd to be bound by historical precedent to type localities of a century ago. The time is ripe for a critical reappraisal of the principles upon which our Precambrian stratigraphy has been established and for a readjustment of our thinking in terms of modern requirements.

What is the practical solution of our problem? The writer has no cure-all proposal. The time-honoured methods of "trial and error" will have to apply, provided that we are sufficiently open-minded to make the necessary adjustments as new factual information is accumulated. We must recognize that much of this factual information is readily available in the field for those who are willing to undertake painstaking and methodical examinations. The work of the field geologist, like that of the infantry in the armed forces, is not glamorous but absolutely essential. The field work should be supplemented by every available practical and scientific approach such as accurate ground control surveys, aerial photographs, geophysical and geochemical aids, and laboratory study. Every use should be made of "dating" methods for establishing the ages of rocks. This provides one of the most useful avenues of approach and could compensate for the lack of fossils in Precambrian rocks.

Conclusions

In conclusion the writer would emphasize certain points and make a few recommendations, as follows:

1. Geologists should realize that the geology of the north shore of Lake Huron is by no means well established. The impression is often gained that this belt should form the basis of Precambrian stratigraphy and correlation. For example, the National Committee on Strati-

graphic Nomenclature appointed by the Royal Society of Canada reported in 1934 as follows (Alcock, 1934, p. 115): "The area deemed best suited for subdividing the Precambrian appears to be the region north of Lake Huron where much geological work has been done and where the succession of events is fairly well understood." It is hoped that this paper will create some doubt as to the conclusions reached in this quotation.

2. A moratorium on the creation of new geographic names for series and formations should be maintained until a reasonably large part of the "Huronian" belt has been re-examined in detail.

3. A critical and detailed study of unconformities is a necessary step in establishing the major divisions of the Precambrian. Few unquestionable Precambrian unconformities have been found, yet the basis of our correlation and stratigraphy depends upon them.

4. The principles and bases of Precambrian stratigraphy and correlation should be under constant review by some competent authority. This body should advise and possibly exercise supervision over the use of specific names for series, formations, and structures. More active Canadian participation in the American Commission on Stratigraphic Nomenclature, or the creation of an equivalent Canadian organization with a division devoted to Precambrian problems might be the start of some organized method of bringing order out of stratigraphic chaos in certain parts of the Precambrian shield. Until this is accomplished, the principles and procedures outlined in the so-called "stratigraphic code" (Ashley *et al.*, 1933), and amendments to it by the American Commission on Stratigraphic Nomenclature, may offer some guidance.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA

VOLUME XLVII : SERIES III : JUNE, 1953

SECTION FOUR

Preliminary Studies of the Biogeochemistry of Molybdenum

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Introduction

PRELIMINARY investigations have shown that some species of trees can take up relatively large amounts of molybdenum even from relatively unimportant showings of this metal.

Variations from normal are apt to be much greater for molybdenum than for copper or zinc. Even the relatively inconspicuous amount of molybdenum which accompanies some types of copper mineralization produces greater anomalies in the overlying vegetation than does the much more abundant copper. These molybdenum anomalies can be detected by field analytical methods. If more detailed work confirms our preliminary studies it is probable that molybdenum will be used as an important path-finder element in biogeochemical explorations for copper and possibly for tungsten and uranium.

History of Investigation

Agricultural workers have demonstrated that legumes, such as peas and beans, and brassica, such as alfalfa and red clover, are capable of accumulating appreciable amounts of molybdenum, even in areas where it can scarcely be detected in the soil. In 1951 one of us (Routley), under the stimulation and guidance provided by Dr. Vernon C. Brink of the Department of Agronomy of the University of British Columbia, commenced a study of the molybdenum content of legume and brassica seeds collected from widely separated areas of British Columbia. This study showed erratic variations in the molybdenum content of the various seeds analysed. However, it was noted (Warren) that some of the seeds highest in molybdenum content came from an area in Central British Columbia known to contain molybdenum mineralization. Kennco Explorations (Canada) Ltd. then provided us with a suite of tree samples taken over a molybdenum showing which they were investigating at that time. The molybdenum content of these positive trees was compared with that of some

similar trees taken from a negative control area. The difference was so marked that we decided immediately to proceed with further biogeochemical studies of molybdenum.

One problem immediately suggested itself. If small amounts of molybdenum could show up so markedly in the vegetation, would the small amounts of molybdenum associated with some copper deposits produce comparable results? By good fortune Kennco Explorations (Canada) Ltd. had in British Columbia just such a deposit and an excellent suite of samples had already been collected. Permission was granted to use these samples and the results were even more gratifying than we had dared to anticipate.

Until this time most of our analyses had been made by Routley with a Hilger Medium Quartz spectroscope under the guidance of Dr. R. M. Thompson, using techniques which we have described previously (Warren and Thompson, 1945). Now, however, it was decided that more precise chemical methods would best answer our needs and one of us (Delavault) evolved an analytical technique tailor-made for our particular purpose. All the samples which had been analysed spectrographically were then analysed chemically and the results were, if anything, even more convincing. We then analysed chemically a few other samples which we had on hand from various other positive and negative areas. The results appeared to confirm the earlier findings. This preliminary paper presents these investigations in tabular form.

Analytical Method

Molybdenum was determined by a combination of the thiocyanate method described by Sandell (1944) and the isopropyl ether extraction described by Ward (1951). No provision is made for interference by large amounts of tungsten. In our own investigations it just happened that preliminary spectroscopic analyses showed that tungsten was not a measurable factor. Furthermore, as far as biogeochemical prospecting is concerned, any analytical confusion which resulted in the discovery of tungsten mineralization where molybdenum had been anticipated would doubtless be regarded somewhat tolerantly.

In brief, our analytical procedure has been as follows. The sample of dried plant material, usually one gram, is ashed at around 600°C. for five hours. The resulting ash is dissolved in warm hydrochloric and passed into a test-tube approximately gauged at 10 ml. using 10 per cent hydrochloric in the jet flask. Then we add successively 1 ml. of 5 per cent ammonium thiocyanate and 0.5 ml. of 10 per cent stannous chloride in 2N hydrochloric. The volume is made up to 10 ml.

with 10 per cent hydrochloric. Next 1.0 ml. of isopropyl ether (less volatile than ethyl ether) is added; the test-tube is closed with a cork stopper, turned upside down, shaken for half a minute at most, and put right side up. The same operation is performed on standards. Standards which carry more than 20 gammas of molybdenum in the 10 ml. are not shaken with ether. Neither are samples which show colours in this range of intensity; they are compared directly with appropriate standards. If faced with comparing nearly colourless ether layers, it is helpful to transfer sample and standard to the thin branch ($\frac{1}{16}$ inch inside diameter) of an U-tube provided with funnels on both sides. If the bottoms of the tubes are immersed in water it is possible to obtain optical continuity acceptable enough to enable comparisons to be made. The use of this thin tube provides a two-inch path through a fraction of a milliliter of the extracting liquid.

Discussion of Results

On the basis of the 140 analyses summarized in Table I there seems good reason to believe that dry needles, tips, or second-year stems of Alpine Fir, Lodgepole Pine, and Creosote Bush tend to contain from 0.1 to 0.5 p.p.m. of molybdenum in areas where there is no recognizable molybdenum mineralization. In the presence of even modest amounts of molybdenum the content of corresponding organs may rise to 2 to 5 p.p.m. and where potentially economic amounts of molybdenum are available the amounts may run to from 40 to 60 p.p.m. (Stout *et al.*, 1951). It is interesting to note that the mere presence of copper does not appear to increase the molybdenum intake. Some of the molybdenum-negative Lodgepole Pine contained high amounts of copper.

Agriculturists have shown that the amount of molybdenum which can be absorbed by plants is determined not only by the absolute amounts of molybdenum available but also by the pH of the soil and the concentration of various other elements in the soil. It has been found (Stout *et al.*, 1951) that, other things being equal, the greatest absorption of molybdenum takes place if phosphate salts are present and the least if sulphates are conspicious. Because sulphates may well be present in the vicinity of altered orebodies it is obvious that biogeochemists should not expect there to be any simple rule for anticipating either the normal or the abnormal amount of molybdenum in vegetation. Nevertheless, even the limited evidence presently available suggests that where there is any significant molybdenum mineralization it may be expected to be reflected by anomalies in the vegetation. Furthermore, the anomalies produced by molybdenum are so much

TABLE I

MOLYBDENUM CONTENT OF ALPINE FIR (*Abies lasiocarpa*)
Parts per million (p.p.m.) dry plant

Locality	*Organ*	*No. of samples*	*Av. value*
A. *Negative samples*			
(*a*) Tweedsmuir Park	Tips	5	0.3
(*b*) Ymir	Tips	2	0.1
(*c*) Ymir	Needles (various ages)	6	0.1
B. *Positive samples*			
(*a*) Molybdenum prospect (central British British Columbia)	Needles	24	65.
	2nd yr. stems	24	43.
(*b*) Copper prospect with minor molybdenum	Needles (various ages)	26	5.
	Needles (various ages)	21	4.
(*c*) As (*b*) but more remote from mineralization	Needles (various ages)	10	2.

MOLYBDENUM CONTENT OF LODGEPOLE PINE (*Pinus contorta*)
p.p.m. dry plant

A. *Negative samples*			
(*a*) Copper deposit with no molybdenum (central B.C.)	2nd yr. stems	11	0.2
B. *Positive samples*			
(*a*) Copper deposit with scattered molybdenum	Needles (various ages)	4	3.
	Stems	2	2.

MOLYBDENUM CONTENT OF GREASEWOOD OR CREOSOTE BUSH (*Larrea tridentata*)
p.p.m. dry plant

A. *Negative sample*			
(*a*) Arizona, remote from mineralization	2nd yr. stems	1	0.2
B. *Positive sample*			
(*a*) Near San Manuel mineralization	2nd yr. stems	4	5.

greater than those produced by comparable amounts of copper (Warren, Delavault, and Irish, 1952), that it seems well worth carrying out further investigations to see if deposits of such elements as copper and possibly tungsten, which in some places may contain small amounts of molybdenum, may not more readily be sought by hunting for molybdenum biogeochemical anomalies than by looking for the more natural but apparently less satisfactory copper or tungsten anomalies in vegetation.

Summary and Conclusions

It is hoped that more detailed investigations will be reported before long. These should negate or confirm our results. If they confirm our findings it should be obvious that biogeochemistry will prove a useful tool, not only in looking for molybdenum occurrences, but also in looking for copper and possibly tungsten deposits, with which even very minor amounts of molybdenum happen to be associated.

Acknowledgments

The Defence Research Board (Canada) and the Geological Survey of Canada have contributed a substantial portion of the funds which made this research possible. Kennco Explorations (Canada) Ltd. has also contributed by carrying out important field investigations, by paying for numerous analyses, and by giving permission to publish some of the results which appear in this paper.

We are also indebted to Dr. O. S. Lovekin who kindly collected the San Manuel samples and obtained permission for us to make use of them.

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